

Frugal Design for Marginal Contexts

Formulating a Systematic Approach and a Design Toolkit

A thesis submitted in partial fulfilment of the
requirements for the Degree of
Doctor of Philosophy

By

Pankaj Upadhyay



Department of Design,
Indian Institute of Technology Guwahati

Assam, India 781039

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Pankaj Upadhyay
(Roll No: 146105016)

Under the Guidance of
Prof. Ravi Mokashi Punekar



Department of Design,
Indian Institute of Technology Guwahati

Assam, India 781039

September 2021

DECLARATION

It is certified that the work contained in this thesis entitled "**Frugal Design for Marginal Contexts: Formulating a Systematic Approach and a Design Toolkit**". It has been carried out by me, a student in the Department of Design, Indian Institute of Technology Guwahati under the guidance of Prof. Ravi Mokashi Punekar for the award of Doctor of Philosophy and that this work has not been submitted elsewhere for a degree.

Date: _____

Pankaj Upadhyay
Department of Design
Indian Institute of Technology Guwahati
Guwahati 781 039
Assam, India

CERTIFICATE

The research work presented in this thesis entitled “**Frugal Design for Marginal Contexts: Formulating a Systematic Approach and a Design Toolkit**” has been carried out under my supervision and is a bonafide work of Mr Pankaj Upadhyay. This work submitted for the Degree of Doctor of Philosophy is original and has not been submitted for any other degree or diploma to this institute or to any other institute or university. He has also fulfilled all the requirements, including mandatory coursework as per the rules and regulations for the award of the Degree of Doctor of Philosophy of the Indian Institute of Technology Guwahati.

Date: _____

Ravi Mokashi Punekar
Professor, Department of Design
Indian Institute of Technology Guwahati
Guwahati 781 039
Assam, India



*Thank you
Amaji for my Life,
Bapi for my Mind,
Joon for my Heart,
And
Tashu for my Soul.*

This is dedicated to all of you.

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Abstract

The foundations on which product design and development it is built is inherently skewed to serve the affluent global population. Existing product design theories do not consider the constraints faced when designing for scenarios with resource limitations and poverty. Nearly 4 billion people in the world live close to poverty and with limited freedom and capabilities. Yet, it is unclear how designers can create meaningful solutions for such scenarios due to a lack of approaches, tools and an understanding of foundational principles.

This thesis examines the subject of 'Frugal Design for Marginal Contexts' to forward the scope of product design in such socio-economic scenarios and equip design teams with the necessary tools. 'Frugal design' is defined as a low-resource intensive design process for developing affordable, optimised, performant and holistic products, and 'Marginal Contexts' (MC) are defined as social scenarios with poor socio-economic conditions where people lack freedom and capabilities.

The motivation for this thesis came from experiences in doing design projects in MC. Several practical lacunae were encountered during such projects, resulting from a lack of clarity about the design process. There were also limitations to applying traditional design knowledge due to its dependency on resource-intensive operations and incompatible working methods. A need for distinct 'thinking patterns', 'systematic approaches' and 'tools' for designing appropriate solutions was felt. Therefore, the research project aimed *"to develop a framework for systematic design of frugal and holistic product concepts and implement it through a design tool."*

The research aim warranted a multi-method approach where several studies were conducted to develop a systematic approach, understand its effectiveness and create a design tool. A total of six studies are reported in this thesis whose outcomes could cumulatively meet the aim and objectives.

It was found that several foundational aspects of the topic were not adequately defined in the extant literature. Therefore, a comprehensive literature review in relevant domains related to frugal design and MC was imperative. Publications from relevant domains were collected, and an extensive review resulted in defining the key terminologies, identifying design guidelines and uncovering the research gaps addressed in the thesis. Additionally, several proposed frameworks for the systematic design of solutions for MC were also uncovered.

The second study followed a case analysis methodology to provide grounded evidence supporting the various design guidelines and recommendations found in the extant literature review. A sample of successful and failed solutions in two related exercises. Analysing successful solutions in MC resulted in the 'focus areas' for design projects and a typology of solutions in such contexts. The second exercise was a unique research activity where a set of 'failed' solutions in MC were analysed. This study led to the synthesis of specific strategies for practically implementing frugal design guidelines in practice, insights on how solutions may fail and ways to assess the complexity of a solution.

Design researchers need to don the practitioner's hat to appreciate the applicability of theories and supports they develop. Therefore, a retrospective analysis of design projects was conducted to establish an exhaustive understanding of frugal design for MC. In this study, four projects were analysed where the researcher played an active role of a design practitioner. The outcomes helped establish the essential requirements for a systematic approach to frugal design and outlined a list of constraints that affect the design process in MC.

Insights from the studies helped synthesise two novel frameworks for a systematic frugal design approach in MC, utilising the insights derived from extant literature review, analysis of case examples, and the retrospective analysis of projects. Additionally, a critical review of existing

approaches and methodologies for designing in MC provided a benchmark for developing the frameworks. The outcomes of this synthesis were **the Frugal Design Conceptualisation (FDC) framework**, a systematic approach for designing holistic and frugal solutions for MC, and **Contextual Evaluation Hierarchy (CEH)** for understanding design constraints and evaluating frugal solutions at early design phases. The thesis also establishes ways of practically implementing the FDC and CEH frameworks in design projects. These frameworks form the foundation of developing a design tool for supporting systematic frugal design for MC.

A known limitation of existing methodologies and approaches for design in MC was identified as a lack of systematic and empirically validated frameworks in the extant literature review. Therefore, it was imperative to assess the effectiveness of the proposed frameworks. The thesis reports a quantitative quasi-experimental empirical evaluation of the effectiveness of the FDC framework using a concept generation exercise and a repeated-measures study design. In the study, concepts generated using the frameworks were compared with those generated without them. The study provided satisfactory evidence that the FDC framework enabled better systematic conceptualisation of frugal solutions for MC.

Similarly, the experiment also helped understand the effectiveness of the CEH framework in the subjective evaluation of design concepts. It was found that the CEH framework could effectively direct a frugal design process and help in evaluating solutions at early design phases. The FDC and CEH frameworks formed a comprehensive and systematic approach to conceptualise holistic and frugal solutions for MC, which could be translated into appropriate design tools.

The thesis presents a state of the art study on the little known and unique phenomenon of 'frugal mindset'. An extant literature review found that Implementing a frugal design approach depended on a unique 'mindset' that went beyond the typical designer skillsets. The phenomenon is termed 'frugal mindset' and, although essential to design in MC, has not been adequately explored. Therefore, 12 experts were interviewed to understand and identify strategies for imbibing a frugal mindset. A framework for understanding frugal mindsets was developed using cognitive psychology theories to help in analysing the interviews and formulate practical outcomes. Analysis of the interviews resulted in unique strategies designers use for imbibing a frugal mindset when executing design projects for MC. The study also uncovered the unique motivations of designers working in MC and their strategies for finding new design opportunities.

The culmination of the research was in the development of a practical toolkit for supporting frugal design in MC. The insights and outcomes from overall research formed the basis for designing and synthesising **FLOW - the Frugal Design Workflow Toolkit**. Synthesis of the FLOW toolkit followed a double diamond approach and extensively employed the FDC and CEH frameworks and specific instruments designed for the experimental study.

The toolkit presents a structured sequence of 'Design Activities' appended with unique tools designed based on specific research outcomes and overall information uncovered throughout the research. These 'Design Activities' were developed based on the FDC framework, making the toolkit suitable for supporting a systematic frugal design approach. Each Design Activity is structured to provide recommended steps, heuristics, suggestions, and tools to support designers and design teams throughout its implementation. The toolkit also incorporates practical steps and heuristics for imbibing a frugal mindset making it unique from all other existing toolkits.

In the final study, the appropriateness of the FLOW toolkit was assessed using a preliminary evaluation of usability and implementability. Overall the toolkit was found to be reasonably easy to use and implementable in practice. Still, the evaluation uncovered specific areas for improving the toolkit, outlining an avenue for future researchers to take this research forward.

The outcomes of this thesis provide clarity on how design teams must approach the development of holistic and frugal solutions for MC. Most crucially, the research work outlines how frugal design differs from a typical design process. A frugal design process involves designing low-resource holistic solutions and deeply understanding their impact early in a design cycle. The process focuses equally on detailing product embodiments and systemic aspects of a solution for its effective implementation. The process incorporates multiple research phases and co-design sessions with various stakeholders in the context.

Overall, the systematic frugal design process reported here can provide practical ways for designers to develop sustainable and meaningful solutions that could improve the well-being of numerous people living in poor socio-economic conditions.

Keywords

Frugal Design, Marginal Context, Design Toolkit, FLOW – The Frugal Design Workflow Toolkit, Frugal Design Conceptualisation (FDC) Framework, Frugal Innovation, Design for Base of Pyramid

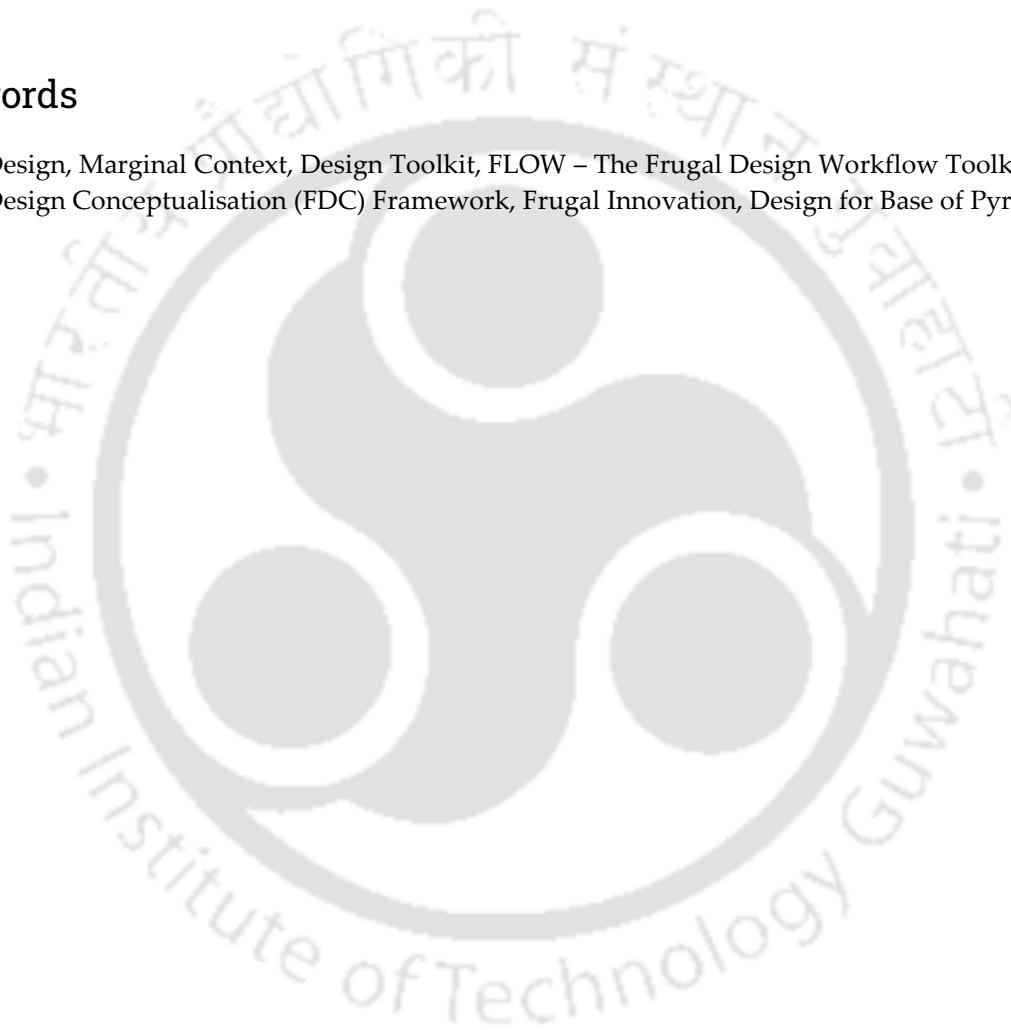


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Abbreviations

AT = Appropriate Technology
ATM = Automatic Teller Machine
BoP, or BOP = Base of the Pyramid
CCi = Closeness Coefficient
CEH = Context Evaluation Hierarchy
DCE = Design Conceptualisation Exercise
DRM = Design Research Methodology
FDC = Frugal Design Conceptualisation
FLOW = Frugal Design Workflow
FVDUS = Feasibility, Viability, Desirability, Usability and Sustainability
IMC = Innovation in Marginal Contexts
MC = Marginal Context(s)
Mfg. = Manufacturing
MNC = Multi-National Corporations
NPD = New Product Development
PDA = Personal Digital Assistant
PHC = Public Health Centre
PLC = Product Life Cycle
PoCT = Point of Care Testing





Chapter 1 Introduction to Frugal Design and Its Foundations

Among many developing countries such as India, there is significant scope for designing products for people living in 'Marginal Contexts' (MC). These contexts are social scenarios with poor socio-economic conditions where people lack freedom and capabilities. Products that can appropriately meet the aspirational needs of this section of users are typically 'low-resource intensive' in their development and usage. The process of developing such products can be called 'frugal design'.

This doctoral research focuses on the subject of 'Frugal Design for Marginal Contexts'.

First, an in-depth understanding of frugal design is established through an extant literature review, a case study of existing solutions and an analysis of design practice. Based on this foundation, the thesis presents frameworks for systematically designing holistic and frugal solutions for MC. Holistic solutions are defined as those which carefully consider the interdependencies in multiple design domains such as product development, service design and dissemination when implementing a solution.

The developed frameworks form the basis for creating a tool for design practitioners to help them systematically implement a frugal design process in a stage-wise manner. The research covers exhaustive analyses and evaluations characteristic of scientific enquiry and presents the findings in eight chapters. The chapters span in-depth literature reviews, analysis of existing solutions and design projects, development and evaluation of frameworks for a systematic approach, and the synthesis and preliminary evaluation of tools.

This first chapter discusses the foundational aspects of frugal design for MC to establish the research directions for the thesis. The chapter presents an overview of the literature review highlighting the key findings, foundational concepts and overall recommendations for the emergent construct of 'Frugal Design'.

The sections of this chapter are divided as follows:

- Section 1.1 frames the foundational topics on which this research is contextualized.
- Section 1.2 delves deeper into the literature surrounding poverty economics, consumption and marketing to define the 'marginal contexts' (MC) and its characteristics relevant to the topic.
- Section 1.3 analyses the literature around innovation in resource-constrained environments. Several relevant terminologies such as *Jugaad*, Frugal Innovation and Grassroots Innovation are also discussed.
- Section 1.4 presents an overview of relevant design-related literature where several existing approaches such as participatory design and product-service-systems design are critically reviewed for their effectiveness in MC.
- Section 1.5 discusses the key findings from the extant literature review and outlines the insights and recommendations for frugal design.

- Section 1.6 lists the research gaps and questions identified and shows the selected questions answered in this thesis. The aim and objectives of the research are also discussed here.
- Section 1.7 describes the research plan, thesis structure and justifies the various studies executed in the research to fulfil the objectives.

Motivations for this research – a personal note

Lest a crucial aspect is missed in the intricacies of the writing that follow, the researcher begins on a personal note by first outlining the motivations for choosing this topic.

“I first began working as an industrial designer at a firm developing products for the mass market. In my approach, I was preoccupied with seeking the ‘wow’ features that mostly included aesthetics and usability. During a visit to my village, I noticed that my grandparents no longer used old kerosene lamps, which consumed much fuel and needed daily messy cleaning. The old products were replaced with low-cost solar LED lanterns that served as a versatile light source for the household. This LED lamp used solar energy, possessed great aesthetics, usability, robustness, and so much more. This product’s ‘wow’ factor was clearly beyond just its features and looks.

What was the underlying design thinking in developing such products? Were there nuances to designing such products that were different from conventional processes? Such questions planted the seeds of curiosity in my mind.

In my engagement with students at IIT Guwahati, I explored how such products can be designed. However, limitations of using existing product design processes soon became evident as the projects progressed. There were very few design supports and tools for developing frugal, appropriate, and sustainable products that promised meaningful solutions to the people in MC. The recommendations and guidelines for approaching such ‘frugal’ design projects were limited in their application for different product types and contexts. I also realised that the complexity of these design solutions depended on supporting socio-technical systems rather than just their embodiment. These experiences also highlighted the importance of design approaches such as participatory design. However, existing tools and methods for such approaches could not be directly applied and were difficult for inexperienced designers.

My urge to design culturally sensitive, unique, and high technology products for marginalised social contexts and the challenges I faced in executing such projects set me on the path of this research enquiry.”

1.1 Framing the topic of Frugal Design

Several relevant literature domains must be consulted to frame the topic of ‘frugal design’ and its applicability to ‘marginal contexts’ (MC). An overview of state-of-art research indicated that parts of the topic were discussed in publications of multiple domains and with varied goals and perspectives. Therefore, a strategy recommended in ‘DRM: A design research methodology’ [1] was chosen for directing the extant review on the emergent topic of ‘Frugal Design’.

DRM suggests creating an Areas of Relevant Contribution (ARC) diagram [1, pp. 81–89] to drive the literature finding process and execute a systematic review. Figure 1.1 shows the ARC diagram with the literature review topics.

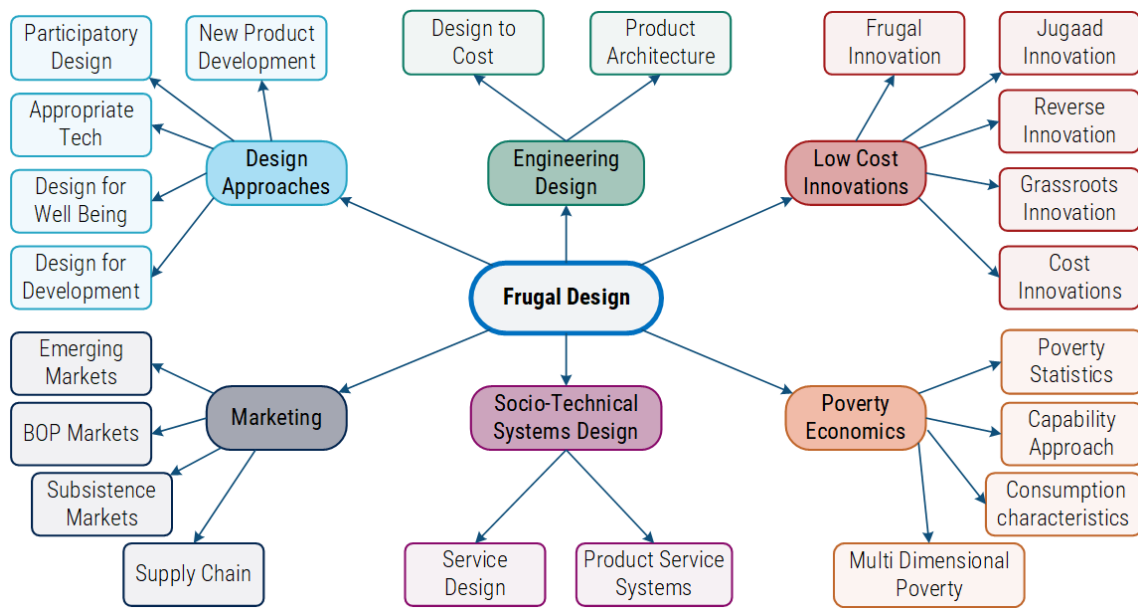


Figure 1.1: ARC diagram for finding relevant domains of literature for search.

The key topics related to frugal design for MC emerged as product development, innovation in marginal contexts, marketing in subsistence economies and poverty economics. Relevant articles in these domains were identified and shortlisted for an extensive review if they discussed one or more of the following topics:

- The various typologies of innovation in the marginalised socio-economic contexts and their characteristics.
- Processes and methods for product design or development in such contexts.
- Factors that affect the design of services and systems in MC.
- Framework, models or approaches for design and innovation in MC.
- Design tools that were used to execute projects in MC.

Although the term ‘Frugal Design’ has only recently been used with the appropriate meaning¹, its central ideas are closely related to ‘Frugal innovation’. Frugal innovation is defined as a process for developing low-cost products and solutions, typically for low-income contexts [2]. Several similar terminologies are associated with innovation in low-income contexts [3]. Therefore, understanding the characteristics of low-income contexts and the associated innovation paradigms is necessary for understanding frugal design. Such information was uncovered in the domain of poverty economics and low-cost innovation literature.

Poverty economics literature also provides an understanding of the capability of the people in low-income contexts. On the other hand, literature on marketing for such socio-economic contexts provides information on the overall environment in which the people live. Marketing literature also provides information related to effective business processes and strategies for disseminating

¹¹ in Scopus database the oldest entry with the term ‘Frugal Design’ in Abstract, with relevant focus of the article is from 2014 [150]

frugal innovations. For example, Sharma & Iyer discuss strategies employed by resource-constrained innovations that can improve the sustainability of supply chains [4].

However, innovation and marketing related literature typically discuss the overall organisational strategies. Literature on product development for low-income contexts, on the other hand, is far more focused on approaches and methodologies. Several design approaches have been suggested for frugal design, such as Participatory design approaches and product-service systems design, each with their benefits. These design approaches and their methodologies must be reviewed for developing a foundational understanding of Frugal Design. Additionally, this literature domain discusses relevant tools and frameworks for design and development.

It is important to consider the unique supply chain and dissemination challenges when developing solutions for MC [5]. Literature on socio-technical systems design can provide insights on such strategies for distributing and scaling up solutions for large populations in MC. Similarly, literature around product architecture and design to cost can provide insights on making solutions 'frugal' and significant cost reduction [6].

Finally, frugal solutions must be approached using board development goals [7] encompassing impact assessment and scaling up the solutions. Literature around the 'Capability Approach' contained some methodologies and strategies for measuring the impact of a frugal solution in marginal contexts [8].

The ARC diagram (Figure 1.1) provides a snapshot of foundational topics related to 'Frugal Design'. An extant literature review then was conducted within these boundaries to derive insights and research gaps. The following sections summarise the findings from the literature review in an attempt to define frugal design for marginal contexts.

1.2 Understanding Marginal Contexts

Today, most strategies for product development, business planning and supply chain of well-designed products and services cater to a small percentage of the affluent global population. Due to this, they seem inadequate and ill-suited for low-resource and low-income socio-economic contexts. Therefore, to effectively design for such marginal contexts, it becomes imperative to understand its characteristics. The most telling characteristic of such contexts is poverty and inequality, and its scale can provide an idea of the challenges in designing for them.

1.2.1 The Scale of Global Poverty

One of the sustainable development goals is to end extreme poverty globally. Extreme poverty is defined as living on \$1.9 a day in 2011 purchasing power parity rates [9]. When measured in 2013, an estimated 767 million people lived in extreme poverty [10]. A more recent estimate from 2017 says that around **647 million** still do [9]. However, the World Bank's is mostly on track in its goal to 'reduce extreme poverty to below 3% of the world population by 2030' [9], [11]

However, if the threshold is increased a little, a sizable global population is still at considerable risk of falling back into extreme poverty [12]. Clearly, despite the reduction in extreme poverty, income

inequality is growing, and the more significant population does not share the prosperity of a country. In addition, the Covid-19 global pandemic has further pressed the brakes on the overall trend of poverty reduction [13].

The World Bank also measures poverty on thresholds of \$3.20 and \$5.50 per day [13]. In 2017, an estimated **1.8 billion people** lived below \$3.20 per day income and around **3.3 billion** below \$5.50 [13]. The number of people living on \$5.50 per day has been nearly the same for the last 25 years [13]. These staggering numbers have had a much slower decline than extreme poverty.

In addition to the international poverty lines, the concept of the societal poverty line is a relative measure used for understanding poverty [14]. The nature of poverty in developed countries is different than in developing countries. It thus makes sense to have separate poverty lines for each country based on their social paradigms. In 2017 the average societal poverty line was calculated as \$7.2 per day (PPP) [13]. Considering this measure, more than **2 billion** people lived in poverty in 2017, and it has hardly decreased since 1990 [13], [14].

One more estimate suggests that the \$10 (PPP) per day income should be considered the threshold for low-income populations [15]. According to this report, an income of \$10 does not allow people to fall back to poverty. Estimates say around **4.4 billion people**, or **71% of the world population**, had an income of \$10 or less per day in 2011 [12].

In India, **363 million** people were below the poverty line in 2011 [16]. The 2014 report by the Indian Planning Commission (IPC) estimates the Indian poverty line at a monthly per capita consumption of INR 972 in rural areas and Rs. 1407 in urban areas (2012 data) [16]. An estimated **30.9% of the rural population and 26.4% of the urban population** is below the poverty line [16]. A family of 5 living in the rural areas could meet the basic needs of survival only at an estimated Rs 4860 per month in rural areas and Rs 7035 per month in urban areas [16].

The disparity in income distribution is also alarming. The graphical plot of the income disparity shown in Figure 1.2 reveals the stark difference between the global rich and poor [17, p. 77].

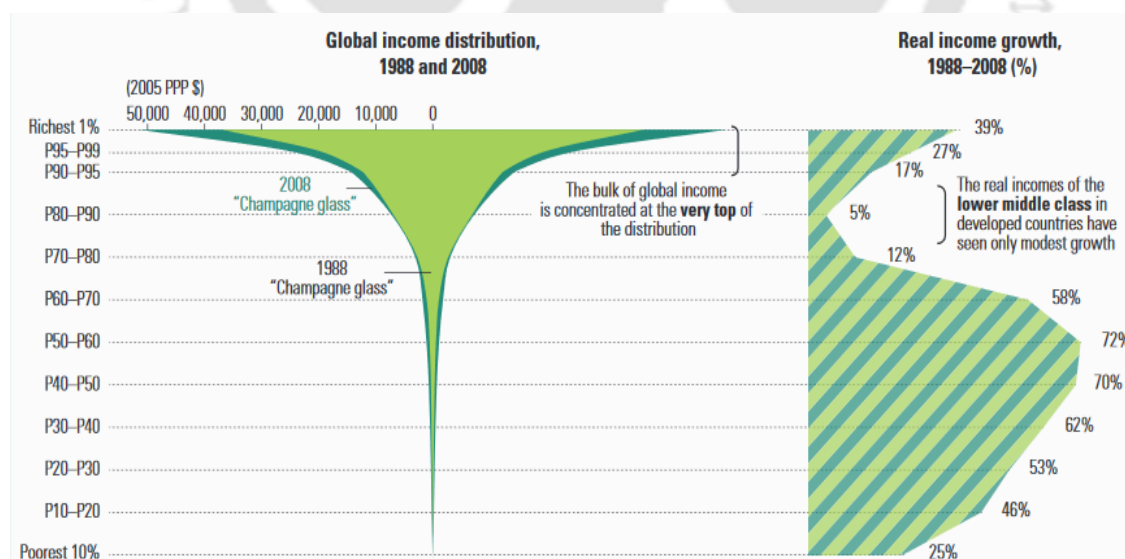


Figure 1.2: Global Income Distribution with respect to % population and rate of growth in their income. Data from 1998 to 2008. Human Development Report 2016 [17].

Going by the different measures, anywhere from **2 to 4.4 billion people** live in poverty. Unfortunately, the income/consumption statistic does not begin to show the plight of people living in such contexts. It is evident that poverty is multi-dimensional, and its characteristics go beyond people's income and consumption metrics.

1.2.2 Multi-dimensional nature of poverty

There are several other ways to look at poverty, and some are arguably more holistic than others. The international poverty lines have difficulty, complexity and uncertainty in measuring the change of income capability (in PPP) over time [11]. Due to this, some additional markers are used to supplement the insights from international poverty line estimates.

One marker directly derived from the income and consumption measurements is called 'the Bottom 40 %'. The world bank has used this characteristic to study how the growth of GDP per capita affects the lower 40% of the population [10]. In other words, if the benefit from the countries growth is shared equitably with the entire population of the country [10].

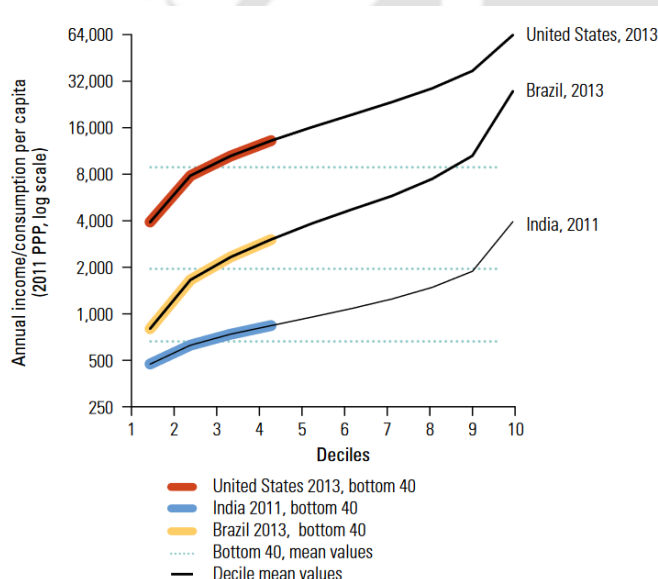


Figure 1.3: Annual income of the Bottom 40 % in India, Brazil and US. Based on World Bank 2015 [10]

Comparing this metric for various countries shows a stark contrast in poverty. For example, Figure 1.3 shows the annual income/consumption of three countries, namely Brazil, India and the US, each at a significantly different living standard of the bottom 40% [10]. The mean income of a bottom 40% Brazilian is equivalent to the 90th wealthiest percentile of someone from India. The same is true when comparing Brazil and the US. The bottom 40% in the US earns about 13 times more than the bottom 40% in India (\$8861 per person PPP in the US and \$664 per person PPP in India) [10]. The top 10 percentile of India barely makes it to the equivalent bottom 40% of the United States. In fact, what is

surprising is that more than 95% of the Indian population lives below \$10 a day PPP (or INR 217.2 per day considering 2019 values)².

Of course, the people in the bottom 40% differ from the rest of the population in various other dimensions as well[11], which brings us to the Multi-Dimensional Poverty Index (MPI). The MPI

² The value of 217.2 is calculated based on the average market exchange rate of 2019 (estimate to be INR 72.4 per USD from <http://www.x-rates.com>) and multiplying the PPP conversion factor (GDP) to market exchange rate (0.3 for 2019 for India from <https://data.worldbank.org/indicator/PA.NUS.PPPC.RF>)

approach imbibes the criticism that income distribution is not the complete way of measuring poverty [18] and was favoured by economists like Amartya Sen and Sabina Alkire [19].

The MPI approach proposes that poverty is related to the dimensions of health, education, and living standards of an individual, not just the income [20]. Each MPI dimension is further subdivided into ten indicators carrying specific weights. To be considered poor on the MPI scale, a person must be deprived in at least one-third of the indicators [21]. The Global MPI is a complementary measure to the international poverty line that shows the extent of deprivation people face in the marginal context [20].

The latest data estimates that nearly **1.3 billion people** (from 151 countries) are poor considering the global MPI indicators [20]. Surprisingly, there are MPI poor individuals within an affluent household. Even within a country's cohort of MPI poor, there are drastic differences, i.e. people are poor at different levels on the different MPI indicators. Moreover, more than two-thirds of the MPI poor population counter-intuitively belongs to middle-income households.

There are profound effects of multi-dimensional poverty. For example, education is thought to be one of the most effective ways of alleviating poverty in large sections [22]. However, even when children have access to education to various social programs, their capability to learn is marred by their poverty in other indicators of MPI [20].

The different methods of measurement yield a different scale of the problem of poverty, each one corroborating the other and positing that the scale may be more extensive than previously thought. Therefore, it is paramount for designers³ to understand the characteristics of poverty to design appropriate solutions for contexts affected by it.

1.2.3 Characteristics of Marginal Contexts

Literature related to marketing in low-income and poor socio-economic contexts provides an avenue to understand the characteristics of poverty relevant for designers. Various terms describe market segments and contexts affected by poverty. The most prominent of them is the 'BOP market segment'. In addition, terminologies such as 'resource-constrained environments', subsistence markets and emerging markets have also been used to describe similar segments. Characteristics of such segments are discussed below

1.2.3.1 Perspective from BOP Marketing Literature

In the Book "*Fortune at the Bottom of the Pyramid*" [23], Prahalad argues that the people who make less than \$2 a day make up a promising market for MNC's expansion plans. The primary proposition is that MNC's could potentially eradicate poverty by actively engaging in business with the poor and making sustained profits in the process [23]. The term 'Bottom of the Pyramid' (BOP) is a euphemism to describe the lower part of a representative diagram of the global income

³ The terms 'designers', 'design practitioners' and 'design teams' have been used interchangeably in this thesis to denote interdisciplinary teams who collaboratively conceptualise solutions for user needs.

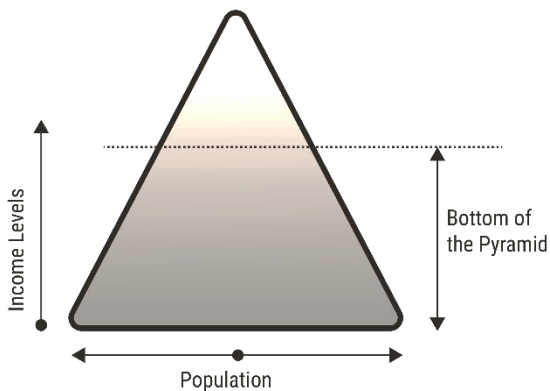


Figure 1.4: Graphical representation of Bottom of the Pyramid.

distribution. (see Figure 1.4. In reality, the distribution will look like the inverted version of Figure 1.2).

Crabtree and Karnani have criticised Prahalad's thesis [24]–[26]. There is also a lack of consensus in defining the actual BOP Market [26], [27]. However, the idea has broadened in recent literature [26], [28] with the proposition is that people at the BOP can be integrated into a solutions value chain as partners and producers for mutual value creation [29]–[31].

Consequently, the indication is that this leads to better income and increased capabilities of the people in the BOP [32]. The latest understanding

of a BOP market is - the group of people with low incomes and limited capabilities who feel socially excluded or humiliated because they do not conform to the ways of the global consumer culture [28].

The literature around BOP markets provides a good account of the characteristics of the population. The people in the context have limited understanding and access to existing products and services that serve the more affluent population [32]. They pay 'poverty penalties', i.e. the same essential services (such as healthcare insurance) are much costlier for them [33]. Due to low income, businesses face low payment rates and find it challenging to provide consistent services [33]. BOP communities nurture social networks and specific cultural habits but are susceptible to superstitions also [34], [35].

There is a significant lack of institutional support from financial and other agencies [32]. This institutional gap affects businesses that operate in them [33]. There is weak governance, corruption, and security concerns that people in BOP have to deal with regularly [33]. Due to the ineffectiveness of institutional rules and governance, many businesses operate informally and outside of law [32].

People in the BOP aspire to a modest and middle-class living. Instead of desiring high end or affluent products and services, they aspire for brands that cater to the middle class [33]. Despite generally low-income, many people in the BOP segment do own assets. These assets, however, cannot be leveraged due to a lack of registrations, regulations and other extra-legal circumstances [32]. In addition, people's requirements in such scenarios are too varied and heterogeneous for any business to employ simple services [33]. Therefore, it is commonly agreed that radically novel business models are needed for operation in the market [33].

The same characteristics that make the BOP markets unique have been regarded as constraints for business models [33], [36]. Furthermore, the business models needed in the BOP are considered complex due to the difficulties in ethically managing the triple bottom line [33].

1.2.3.2 Perspective from Subsistence Markets Literature

The critical distinction between 'Subsistence Markets' (SM) and BOP markets, according to Vishwanathan and Rosa [37], is that SM considers a more micro-level view that is not highlighted

in BOP discourse. They defend their use of the term, saying it conveys a broader understanding than BOP markets and is not 'patronising and demeaning' like the BOP term [38].

A micro-level view considers the overall economic indicators and the context's social, interpersonal, and individual factors. Unlike the connotation in BOP markets, subsistence markets can exist in advanced economies [38].

Such contexts are predominantly male-dominated with consistent and pervasive uncertainty due to illness, unexpected birth or death, marriages or seasonal changes [34], [39]. Still, many subsistent families prioritise children's education, according to Vishwanathan et al. [34]. Interestingly, the MPI reports suggest that the children education budget is the first to get truncated during income uncertainties in poor households [20].

People in subsistence communities find support from local shops, communities, NGOs and other philanthropic organisations for financial assistance and savings. The most striking characteristics in subsistence markets are the buyer and seller relationships [34]. Consumers in this market rely on credit from shops in local networks and word-of-mouth reviews [39]. Interestingly, products and services are considered strategies for coping with difficulties and people are interested in them only if they are compelling alternatives to local and expensive products [39].

1.2.3.3 Perspectives from Emerging Markets Literature

'Emerging markets' is the broadest term used to describe the low-income market segment and is used primarily to discuss developing economies as a whole. The term was coined in the 80s to describe lower-income economies as a whole [54]. Brazil, Russia, India, China and South Africa (BRICS) are considered its main constituents [40], with India and China being considered most promising [3]. The demand for goods in emerging markets has been projected as high as US\$56 trillion [3]. It is not surprising that nearly 1300 MNC's are operating in India alone [41].

Overall the literature regarding emerging markets is vast (Scopus.com produces over 15000 hits for the search term "emerging markets"), spanning topics of innovation, supply chain, corporate governance and entrepreneurship, to name a few. Still, the importance of medium and small-scale enterprises stands out as a relevant characteristic of such markets.

Medium and small scale enterprises (MSME) are the leading players within emerging markets [42]. MSMEs are uniquely positioned to provide frugal products and services in emerging markets and are possibly the primary drivers of frugal innovation [43]. However, they are considered less innovative and more focused on surviving the market [44]. There seem to be some similarities between the constraints faced by the people in BOP and MSMEs in emerging markets. MSMEs are unequally hurt by the lack of infrastructure [58], have difficulties in operation due to weak governance [44], lack financial credit [44]. Still, a 2011 estimate suggests that nearly half of the manufacturing output in India and 40 per cent of exports are due to MSMEs [44].

1.2.3.4 Characteristics of Consumption in Marginal Contexts

The consumption habits of MC are different from that of other national and international consumers [45]. Reports suggest that although accounting for only 20% of the global population, developing countries are responsible for 80% of the total consumption [46]. People in the BOP

contexts aspire to specific consumption patterns not just for sustenance but also to avoid social exclusion, shame and humiliation [28].

Banerjee and Duflo's [47] seminal book on the '*Economic lives of the poor*' drives home the point that the poor have unhealthy spending habits driven by their need to belong. Households spend more on marriage, festivals, funerals and other religious [47]. Banerjee and Duflo[47] equate this spending to be similar to the need for entertainment, a dimension that is essentially not covered in the poverty studies. It could also be that the strong social ties and networks put peer pressure on the people to spend on such luxuries (see [32], [48], [49]).

The poor are also severely malnourished despite spending around 60% on food[50]. An Indian report suggests that people in MC consumed significantly lower calories than recommended [16], [47]. Such lack of nutrition causes health issues, anxiety and stress to the level that it hampers daily working [47]. Still, the bottom poor spent around 5 % of their income on tobacco and alcohol [47].

Although not conclusive evidence, we see that the population has needs beyond just food, health and shelter. Simultaneously their consumption habits are neither rational nor dependent on income. It is unwise to think that the people are in total control of purchasing goods and services.

Therefore, Designers have to be more cautious and ethical when designing solutions that are accessible to people without becoming a burden on survival and sustenance. Designing aspirational solutions may be counterproductive, putting undue pressure on people to spend on the solutions before securing necessities. Thus, it becomes a part responsibility of designers to develop sustainable and ethical means of delivering the solutions. One way to do this could be to carefully consider the effects of the solution on people's capabilities.

1.2.4 What is a Marginal Context?

The review highlighted that it is best to define MC by the characteristics of people's lives and their environment rather than specific statistical metrics. Table 1.1 provide an overview of the characteristics of MC:

Table 1.1: Characteristics of People's lives in Marginal Contexts.

Categories	Characteristics of the People's lives
Lack of Affordability and Income	<p>People have low incomes and lack equality compared to the affluent population [13].</p> <p>Their income level is lesser than the income of the bottom 40% [10], and they are at risk of falling into poverty. [15]</p> <p>They sometimes pay 'poverty penalties' making products and services more costly to them [33]</p>
Lack of Capabilities	<p>They have limited capabilities, freedom and may face humiliation due to their livelihoods [28].</p> <p>People may have low literacy and numeracy skills [38]</p> <p>Children in such contexts have reduced learning capability due to other aspects of poverty [20].</p>

Uneven Consumption Practices	<p>They have unhealthy and unreasonable consumption habits. There may be some reliance on addictive substances and alcohol [47].</p> <p>They may be malnourished despite disproportionately high percentage spending on food and sustenance [16], [50]</p> <p>They face challenges due to unexpected and seasonal expenses [34].</p> <p>They face peer pressure that leads to unreasonable spending habits [32], [48], [49]</p>
Lack of access	<p>People lack access to infrastructure and institutional support [22].</p> <p>They lack access to necessities such as health, sanitation, water, education, internet, electricity, housing, fuel and assets [11], [21].</p> <p>They have limited understanding, information and access to products and services [32]</p>
Strong Social Ties	<p>They are part of a strong community and social networks [34].</p> <p>They have strong cultural bonds and support networks [51]</p>
Others	<p>People aspire for a middle-class living [33].</p> <p>Contexts may be male-dominated and patriarchal. [34], [39].</p>

Table 1.2: Characteristics of Environments in Marginal Contexts.

Categories	Characteristics of the environment
Challenge of payment	Due to low affordability, businesses face low payment rates, due to which they struggle to provide consistent services [33].
Lack of Institutional support	<p>There is a significant lack of institutional support from financial and other agencies [32].</p> <p>There is weak governance, corruption, and security that the people have to deal with regularly [33].</p> <p>Existing assets cannot be leveraged due to a lack of registrations, regulations and other extra-legal circumstances [32].</p>
Local Channels and Networks	<p>Local shops and establishments are a source of credit and financial support [34].</p> <p>There is an interactional and network-rich nature of buyer and seller relationships [34].</p> <p>People rely more on references from their networks than general marketing campaigns [39].</p>
Others	Medium and small scale enterprises (MSME) are the leading players in the context [42].

Around 71 % of the global population faces poverty in one form or another [12]. Still, defining marginal contexts as a percentage of the global population is reductive. Poverty is contextual and depends on geography, economic background and access to goods and services.

People living in poverty lack the capabilities to act on their freedoms and pursue their livelihoods [21]. Moreover, lack of capabilities in one aspect affects their capability in others. Even if they earn above the poverty thresholds, they may face erratic income and uncertainties due to seasons,

diseases and other unforeseen events in life. The Covid-19 is one such example that disproportionately affected the low-income population by severing their livelihoods.

Additionally, the environment in which poor people live also contributes to their lack of access and reduced capabilities. Such scenarios lack effective governance and have high corruption, making it difficult for organisations and solution providers to serve the people. Furthermore, people in these scenarios have limited affordability, literacy and skill to engage in entrepreneurial activities. Due to such problems, they also find it challenging to access better solutions for their problems. Despite being a large consumer segment with high consumption needs, people living in such scenarios have unhealthy spending habits. Such practices can be attributed to their low literacy and a lack of access to relevant knowledge.

Despite their hardships, the people in MC are part of unique social networks. These social networks are a strength of the people and should be understood and leveraged when providing solutions. These networks can be leveraged for financial aid, information and income generation activities.

Based on the understanding of poverty and its characteristics, we can define **Marginal Contexts (MC)** within the boundaries of our research as follows:

Marginal Contexts are social scenarios within a specific geographical boundary where the people have low income, low capabilities, low freedom and lack access to infrastructure and institutional support.

In this definition, income and capabilities should be low compared to the country's average levels. Therefore, MC is not a group of people under a certain income threshold, it can exist even in developed economies, and one geography cannot be directly compared to others. i.e. MCs in India do not share the same characteristics as MC in the US.

1.3 Innovation in Marginal Contexts

Innovation is tied to the design process because designers peruse product, process or service novelty during their development. Therefore, a designer is an integral part of the innovation process, and it becomes imperative to analyse literature related to innovation in MC.

A plethora of literature is available on innovation, which primarily revolves around how firms or organisations can build capabilities for delivering novel value from the resources (human, material or process) that exist within. The review focused on a subset of this literature about how individuals and firms can innovate for the MC. Specifically, the literature around 'Jugaad Innovation', 'Grassroots innovation', 'Frugal Innovation' and 'Reverse Innovation' was reviewed. Several other paradigms for Innovation in Marginal Context (IMC) exist, such as *Shanzai*, Inclusive innovation, Indigenous innovation, Constraint-based innovation, Blowback innovation and Trickle-up innovation. (Agarwal et al. [52], Brem and Wolfram [3], and Soni et al. [53] provide a review of some of the terminologies).

Here our efforts are concentrated on an in-depth understanding of a few IMC terms related to the design of products and services (rather than markets and processes). These selected terminologies

present distinct views of the innovation process, which was fruitful for drawing relevant insights. Moreover, the most significant portion of the IMC literature is concentrated around these terms [3].

Table 1.3 provides a short definition and references to some notable IMC paradigms.

Table 1.3: Definition of prominent Innovation in Marginal Context (IMC) terminologies found in the literature.

Terminology	Definition	Key References
Jugaad innovation	These are Improvised solutions and approaches to solve problems presented by marginal context, typically by people in the context. The learnings derived from Jugaad innovations have been translated for organisations by Radjou et al. [54]. Similar to Bricolage.	[54], [55]
Bricolage	A mindset and attitude of making do with available resources for developing affordable solutions for marginal contexts. Aimed at entrepreneurship in marginal contexts. Similar to Jugaad.	[56]
Gandhian Innovation	It is an amalgamation of Gandhian philosophy with innovation theory. Solutions adapt technologies developed by people and scale them to serve a large population in MC. Semi philanthropic in nature focused on scaling local technology to serve the mass. Similar to grassroots innovation.	[57]
Grassroots Innovation	It is an approach to developing solutions in collaboration with creative people in marginal contexts. People's original creative ideas are adapted and systematically developed to become marketable products that serve a larger market. Similar to Gandhian Innovation.	[58]
Frugal Innovation	Solutions that are significantly low cost than existing solutions focus on only a few core functions and are optimised to perform adequately for the needs in the context. It is a broad and encompassing terminology focusing on systematic processes to develop solutions for marginal contexts.	[59]
Catalytic innovation	An approach that focuses on creating social change by disrupting existing markets. The focus is on creating networks and infrastructures that work as catalysts to support novel solutions in marginal contexts. Similar to disruptive innovation.	[3]
Resource-Constrained Innovation	It is an approach to developing new solutions when resources are scarce, e.g. in marginal contexts. The approach focuses on balancing cost and performance objectives and developing affordable, mass-market solutions. It is superseded by the term frugal innovation.	[4], [60]
Disruptive Innovation	Innovative solutions disrupt the active players in a market by presenting solutions that perform better than existing solutions at a significantly lower cost. Similar to Catalytic Innovation and superseded by Reverse innovation.	[61], [62]
Reverse Innovation	Solutions have been primarily developed in or for emerging markets and are sold in developed countries due to their unique and meaningful value propositions. Closely related to Disruptive innovations.	[63], [64]

1.3.1 Jugaad Innovation

Brem and Wolfram[3] define *Jugaad* innovation as:

“An improvisational approach to solving one’s own or others’ problems in a creative way, at a low cost, in a short amount of time, and without serious taxonomy or discipline applied by people at the BoP as a result of poverty and exigency.”

Jugaad is thus understood as an improvisational approach to designing solutions in resource-constrained environments. It is a grass-root level practice for innovating processes and products, evolving out of the sheer necessity created by a lack of access to capital, resources, and infrastructure.

Jugaad innovations have been propagated as a solution for the unstructured BOP markets [54]. It is proposed as a means of developing frugal products, businesses and socio-technical systems [65]. Unfortunately, innately *Jugaad* has negative connotations due to its etymology. It is considered a means of getting things done by cobbling and hacking things together [66] or using shady and non-legal means for administrative things [67].

Thus, *Jugaad* arises from a lack of infrastructure and an apathetic administration in solving the problem of the people [67]. *Jugaad* and such concepts (Shanzai, Bricolage [52]) show that people are driven to solve their problems themselves when faced with constraints. These constraints are triggers for creative problem-solving. However, due to the lack of resources, most of the solutions originating from *Jugaad* are rudimentary. Moreover, there is no systematic process and taxonomy, making it difficult to replicate [3].

Authors have tried to distil the *Jugaad* mindset and adapt it to an organisational setting [54]. Translating *Jugaad* into the management vocabulary redefines the term as a low-cost and quick-fix solution that circumvents existing resource constraints [67]. Radjou et al. [54], in their book, present six principles to simulate *Jugaad* innovation in an organisation. These are 1) being Frugal, i.e. cautious exploitation of all resources, 2) being Flexible, i.e. easy adaptation to changing constraints, 3) developing simple, easy to use, easy to make and easy to deliver solutions, 4) using intuitive approaches to finding solutions, 5) leveraging constraints into opportunities and strengths, and 6) implementing solutions through appropriate business models. Thus, ‘*Jugaad* Innovation’ can be understood as a mindset proposed for organisations to utilise resources mindfully when developing solutions for MC [3].

The nature of *Jugaad* innovation restrict their adoption and spread since they are more akin to Do-It-yourself projects rather than goods that an organisation can trade. By design, such solutions do not consider efficiency, comfort, human safety and sustainability [54][68][3]. Furthermore, *Jugaad* is a problem-oriented approach and not necessarily a product-oriented approach [3].

1.3.2 Grassroots Innovation

There is some similarity between Jugaad and grassroots innovation. Grassroots innovations define solutions developed by the poor themselves to solve an individually faced problem. However, there is a structured process to grassroots innovation. It focuses on turning the rudimentary solutions developed by people in marginal context into marketable products through collaboration and networking [69]. Therefore, Grassroots innovation is a movement where established agencies collaborate with creative people in the MC to develop new products and create entrepreneurial ventures [58].

Seyfang and Smith [70] define grassroots innovation as:

“networks of activists and organisations generating novel bottom-up solutions for sustainable development...that respond to the local situation and the interests and values of the communities involved”

The presence of committed agencies, activities, and organisations to create sustainable development is the centrepiece of this IMC [70]. Grassroot Innovations typically employ locally available materials and resources judiciously, leading to sustainable usage [70]. Grassroots innovation also creates income-generating and entrepreneurship opportunities for the innovators and people in the MC [58].

In India, the Honey Bee Network, led by Prof. Anil Gupta, is considered a prime example of the grassroots innovation movement [69], [70]. The organisation catalogues novel solutions developed by local innovators and makers. They then liaise between manufacturers, organisations, designers, universities and other interested agencies to develop these solutions into marketable products [58]. They also support the local innovators to establish entrepreneurship ventures to sell the products and protect intellectual rights.

The issue with Grassroots innovation itself is its generalizability. Due to its nature of being tailored to a particular community, the problems may be unique to certain geographies or MC [71]. Furthermore, there is difficulty in supporting it through structured policy since the main players are not necessarily large businesses and MNCs [71]. Although the Honey Bee Network presents a fascinating case, such endeavours are rare and difficult to replicate.

Still, grassroots innovations are considered ‘incubators for social change’ [71]. Additionally, since there is a philanthropic and voluntary nature to the involvement of various actors, sustaining grassroots innovation endeavours is a challenge [70]. Other issues that plague Grassroot innovations from reaching a critical mass are low financial support, internal disputes, political stand, and lack of local support [71]. Thus, both *Jugaad* and grassroots innovations seem to happen without support from formal institutions and remain operational at the local level only [53].

1.3.3 Frugal Innovation

Several review papers have been published that try to understand Frugal Innovations (FIs) and other innovation paradigms in the marginal contexts [52], [72]–[74]. Unfortunately, the haphazard evolution of FI literature has created some confusion in a clear understanding of the concept [73]. There are two crucial views with which emergent literature understands FI [75].

The first perspective is that FI is a ‘process’ that prescribes altering existing practices to achieve new strategies, business models, value chains and organisational practices. The other perspective is that FIs are ‘outcomes’ that are low cost and target MC, i.e. products, solutions, technologies and services. The latest understanding of FI as ‘outcomes’ is based on the work of Weyrauch and Herstatt [59]. They define FIs as solutions where three criteria are simultaneously met:

- 1 The solution has a **significantly lower cost** to the consumer (at least one third) than any existing solutions available in the context or their current practices.
- 2 The solution only **focuses on a set of core functions** essential for fulfilling the need
- 3 The solution **performs optimally** to meet the people needs adequately and is not overdesigned.

Furthermore, it is agreed that FI can be initiated by all kinds of agents such as MNCs, startups, individual entrepreneurs, or grassroots innovators and are primarily targeted towards poor people living in both developing and developed economies [75]. This makes Frugal Innovation the most suitable topic to derive insights to create a systematic ‘frugal design’ approach.

FI can therefore be understood as a broad concept [73] to describe most forms of low cost and resource-constrained innovation for the MC and can exist in both developed and developing economies. Still, FIs have to be ‘homegrown’ since they cannot be derived from resource-intensive western counterparts [76]. Furthermore, over time, FIs will attract affluent customers who may choose such solutions because they are cheap and adequately meet the basic operational criteria [76].

Some authors have attempted to draw parallels and relationships between FI and other typologies of IMC. For example, Soni et al. [53] argue that FI combines the characteristics of Jugaad, Bricolage, Gandhian and disruptive innovation. They assert that a mindset change similar to jugaad and Bricolage, a process similar to ‘frugal engineering’, and an outcome change similar to disruptive innovation is needed for FI. Others have also drawn parallels to Cost innovation, Good enough innovations and Reverse innovation [2], [77]. However, FI is distinctly different from reverse or grassroots innovation since its primary initiators are organisations & agencies, and not individuals.

FIs are believed to be promising for social and ecological sustainability due to their focus on providing affordable solutions for pertinent problems in a social context and judicious utilisation of available resources [75]. However, some studies are cautious with this viewpoint saying sustainability benefits are only spillover effects, and sustainable development is not necessarily a primary focus of FIs [75].

One of the crucial criticisms of FIs is that of the ‘rebound effect’. Despite FIs being potentially more sustainable solutions, their affordability makes them accessible to a large population. This accessibility could cause high consumption, drive up production and resource utilisation and eventually negate any positive sustainability benefits due to the low resource intensiveness of FI

[75]. Furthermore, if the end-of-life of FI solutions is not planned correctly, they may cause large waste generation. Therefore, any systematic process for FI should consider a solution's lifecycle and incorporate appropriate sustainability assessments.

The main impeding factor for FI seems to be diffusion and distribution [78]. In most MC scenarios, people are slow in adopting novel FI solutions due to literacy, understanding, and lack of trust [79], [80]. The lack of established legal and governmental frameworks also work against FIs [2]

Successful frugal innovation can be developed by rethinking production processes, business models and innovation cycles, along with proving extreme value-for-money goods at radically low cost, using a 'clean-slate approach', 'reconfiguring value chains' and 'an attitude of parsimony' [4], [53], [81], [82]. Some believe that lack of resources help organisations develop better FIs by working as creative constraints [76]. A pivotal factor for the success of FIs seems to be a deep collaboration with local people, entities and agencies [83], [84]. Furthermore, successful conceptualisation, development and deployment of FI outcomes should be done close to the intended MC [85]. Successful FI outcomes cannot be just defeatured high-end products; they need architectural change and unique features suited to the context [2]. Creating Successful FI also need a unique mindset for the individual [53] and a unique culture for the organisations [68].

Soni and Krishnan [53] suggest that developing Frugal innovation requires a frugal mindset. The idea of a frugal mindset is interesting since it indicates some inherent quality a designer needs to imbibe to develop FIs effectively. Like the frugal mindset, Pansera and Sarkar[86] also mention the need for a "bricolage attitude" for entrepreneurs working in MC.

Some authors have attempted to develop systematic processes for creating FI [82], [86], [87]. Rao [82] suggests that FI development should follow classical approaches and then optimise the solutions by looking at the constraints in the context and parameters of 'frugality'. On the other hand, Agarwal et al. [91] suggest a constraints-oriented approach to developing creative solutions where the root cause of constraints for FI development are identified, which are then translated to design requirements upon which prototypes are developed. Weyrauch et al. [87] present a four-stage systematic methodology for developing FI, which they term the objective-conflict-resolution (OCR) approach. Their approach focuses on identifying conflicts between requirements and objectives for frugal engineering.

The above methodologies are some of the few existing systematic methodologies for developing FI, but they seem far from holistic. Holistic methodologies are those that can help designers consider the impact of solutions on MC from several different points of view and uncover the interdependencies between aspects such as product development, service design and dissemination as the project progresses.

For example, Rao's [82] model would need considerable development time since it depends on completing the classical NPD approaches before making the solutions frugal. Agarwal et al.'s [86] model is restricted to identifying constraints and root causes that hinder the design but does not include overall product lifecycle aspects. Weyrauch et al.'s [87] model is similar to TRIZ and focuses on creating novel product architectures but does not consider FI's equally important strategic aspects. Therefore, a holistic methodology for FI is needed, considering the several guidelines of FI and mitigating the constraints faced when developing solutions in MC. Such a methodology must consider the strategic aspects such as service design, dissemination of outcomes, product development and highlight the interdependencies between such aspects.

1.3.4 Reverse Innovation

Reverse innovation is a transferal of innovative and novel solutions designed in emerging and developing countries to developed countries. Govindarajan and Trimble [88] have been the leading proponents of the construct.

Govindarajan and colleagues presented that there was indeed significantly creative clout in the developing countries, and they indeed were able to develop promising solutions for their needs [63], [88]–[90]. They argued that innovation in the developing markets had a unique advantage due to which the regular incremental innovation process, which MNCs typically banked on, could be significantly disrupted.

Emerging countries follow a different pattern of innovation and have the advantage of 'leapfrogging' and solving old problems with newer technologies [63]. Furthermore, these technology applications could find new use in the developed countries and thus result in a reversal of the flow of innovation. This reversal was termed Reverse innovation. Zeschky et al. [2] define Reverse innovation as follows:

“reverse innovations are cost, good-enough, or frugal innovations that find a market among customers outside of the emerging markets at which they were originally targeted.”

One of the most prominent examples of reverse innovation is a low-cost ECG device and a portable ultrasound machine by General Electric (GE) [90]. Unlike the existing products, this ECG cost a fraction of the price of existing solutions and was developed for markets like India. However, GE could modify and sell it in more developed markets and disrupt the competition after its success. Unlike their previous counterparts and contrary to the conventional logic, the product was designed to be compact, portable, and good enough. The precise properties that lead to the product's unique selling propositions in the developed markets [63]. A point to note is that not all reverse innovations are initially targeted towards low-income contexts. Several products were initially aimed at the middle classes, albeit in developing economies [91]. Even if that is the case when such solutions were transferred to developed countries, they ended up serving the MC in those countries [91].

There are clear indications from various reviewed cases that frugal innovations have the most potential to eventually get transferred to developing countries and become reverse innovations [2]. Moreover, due to their foundations in grassroots, frugal and cost innovations, reverse innovations are considered good alternatives for sustainable consumption and development, especially in developed countries [91]. However, pursuing reverse innovation needs a foothold in multiple geographies, making reverse innovations a challenge for smaller organisations[89].

Still, the phenomenon of reverse innovation indicates that frugal solutions can have a global impact on sustainable development. Frugal solutions can be modified suitably to serve multiple MC across the globe and do so while consuming limited resources in use and development. Therefore, a frugal design approach for MC is an important piece for designing solutions for global sustainable development.

1.4 Design in Marginal Contexts

Typically design approaches have been devised for supporting product development in an organisational or institutional setting [92]. However, our literature review suggests that such methodologies cannot be directly implemented into MC due to the context's inherent constraints and resources limitations [7]. Such challenges for implementing typical design approaches in MC are highlighted in this section.

A review of the existing NPD methods suggests that they are either product or organisation centric and concentrate on technical problem solving rather than the social aspects of design [93]. Scholars such as Victor Papanek and Buckminster Fuller had suggested that any design should be for the good of the people and that people should be the loci of a design process [94]. However, NPD processes implemented in organisations do not implement such suggestions to the greatest extent possible. Mostly the user involvement in NPD processes is limited to requirement gathering and usability testing [95]. However, the review of IMC literature strongly suggested that people should be closely involved in the development process as co-designers [83], [84], [96], [97].

Fortunately, emergent design approaches such as human-centred design and co-design have started incorporating users more deeply into the process[98]. As a result, tools and methodologies of the classical NPD approaches have been updated to reflect this viewpoint. In these newer methods, significant stress is on understanding the user, lifestyle, and context in which they live [99]. Still, few approaches have been developed explicitly for MC. Here some prominent design approaches are analysed to understand their adequacy for the MC.

1.4.1 A Note on Classical Design Approaches

Before discussing specific approaches for design in MC, a brief look and the historical evolution of the typical new product development (NPD) approach is essential. This understanding provides us with a much-needed perspective on the limitation of such approaches for MC.

There are countless systematic approaches prescribed for the design of new products. However, three prominent texts are highly cited and provide a comprehensive understanding of the product design and development process, each with a distinct focus and flavour. These are '*Product design and development*' by Ulrich and Eppinger [92], '*Engineering Design Methods: Strategies for Product Design*' by Nigel Cross [100] and '*Engineering Design: A Systematic Approach*' by Pahl et al. [101]. These texts can be considered classical design approaches due to their prolific use. Furthermore, newer design approaches build on these classical models by appending them with specific aspects that are considered lacking.

A closer observation of the text by Phal and Bietz [101] suggests that the design methodology is concerned with developing technical systems of medium to high complexity. Where Phal and Bietz [101] provide a technical systems-oriented approach to systematic engineering design, Ulrich and Eppinger[92] provide a generally applicable methodology for product development within an organization. Cross [100], on the other hand, presents a heuristic model that can be used to describe or drive any design activity. Cross presents an iterative four-stage design process of exploration, generation, evaluation and communication[100]. Barring a few other depictions (e.g. March's model [92]), most classical approaches describe the design process as a sequence of phases.

Typically, these phases can be summarised as iterative steps of problem understanding and decomposition, creative problem solving, and concept detailing.

Analysis results indicate that classical approaches have evolved out of necessity for designing technical systems manufactured in industrial and commercial settings. Due to this, the theory of product development has always been either product (i.e. the designed artefact) centric or organisation centric and not adequately user-centric [7]. Consequently, classical design approaches gravitate towards technical solutions for well-described engineering problems rather than holistic solutions for ambiguous social needs. Even the tools prescribed in these approaches focus more on creative technical solutions rather than a deep understanding of the user's context (e.g. morphological charts [101, p. 184], function structure modelling [101, p. 216] and quality function deployment [101, p. 520])

Classical design approaches inherently assume that the organisations have all necessary resources and that the environment is conducive to product development. Users are considered 'Customers' to whom the products would be sold and for whom value is created without necessarily considering their capability improvement or sustainable development. Moreover, classical approaches do not inherently consider cost reduction or low resource consuming design solutions.

Newer approaches in design broaden these classical approaches and solve many of the limitations[98]. These are called human-centred design approaches due to their clear focus on the people's needs throughout the development process. Approaches such as co-design, for example, include users as contributing members in the design process[102]. Furthermore, approaches such as product-service systems design take a broader perspective considering the entire socio-technical system as part of the product being developed.

1.4.2 Product Service Systems Design

Product service systems (PSS) is a market and business proposition that increases the accessibility of the product and also extends its functionality by incorporating additional services [103]. In traditional development models, products are directly sold to consumers for use. Manufacturers do not necessarily consider the end of life effects of the product. PSS offers a transformative business model by integrating 'products' and 'services. In a PSS model, the manufacturers are 'service providers by retaining ownership of the product and selling the 'services offered' to consumers. Thus, the unit sold to the customer is not the product but 'a unit of use' of the product[104].

PSS are considered more sustainable since the manufacturer owns the product and is motivated to maintain the product for as long as possible, thus extending the product's lifecycle [103], [105]. A PSS breaks the link between economic success and material use and reduces environmental impact [106]. The possibility of providing high technology solutions to people at lower costs by selling the 'service offered' instead of the product itself makes it a promising approach for use in MC [107].

PSS recommendation suggest the integration of user and context-specific requirements into the process [108], [109] which is one recommendation for innovating in MC [83], [96]. Furthermore, Tools for PSS design can also be easily implemented in the MC [110]. Furthermore, the PSS business model has a huge impact on the affordability of a solution and its life cycle. Therefore, PSS

design methodologies provide a good framework for specific design processes for MC, which has resulted in some interest in recent literature [30], [35].

However, Jagtap and Larson[30] outline some issues in the successful design of PSS for MC. They say that a lack of appropriate knowledge of the business operation, regulatory frameworks, infrastructure, lack of relevant skills and access to financial services are key hindrances to successful PSS implementation in MC. Since people at MC have limited access to financial services[111], they may find it difficult to use pay per use models for regularly used products since their financial inflow is erratic [47].

Another crucial issue to tackle in PSS design for MC would be the difficulties of dissemination [103]. Even for PSS solutions in regular contexts, the habit of owning a product is hard to shed [105]. Successful PSS dissemination in MC needs to consider behaviour change of the consumers since the ownership of products remains with the service providers. In addition, there may be trust issues with the business model and PSS design that need to be overcome for effective dissemination [36]. There is also a challenge in figuring out an effective way of integrating the people in MC into the value chain of the solution. These difficulties are further exacerbated since people more stringently adhere to their culture, traditional practices, and established working methods [76]. A way of circumventing these difficulties and finding novel solutions to mitigate them could be by getting immersed in people's lives and involving them as partners in the design activity [112].

Still, there are also indications that PSS implementation can increase job opportunities and enhance skills in MC [111]. The PSS methodologies could also help to make products for MC more sustainable [103]. PSS models are also promising if the solutions are high technology which would otherwise be difficult for people to afford since the '*servitization*' of the product offsets the burden of cost reduction [109]. It also potentially reduces the burden on designers to develop groundbreaking and low-cost product architecture redesigns for drastically reducing product costs.

The main issue with PSS design approaches for suitability in MC is that these do not consider the product embodiment to a high degree. Instead, most PSS design approaches concentrate on developing sustainable systems for implementing a '*servitized*' product and the '*products*' are typically developed using traditional NPD methods. There may be situations where specific system-level requirements warrant specific design features in the product. Capturing such requirements and incorporating them into the architecture is not adequately addressed in PSS approaches.

1.4.3 Design for development and wellbeing

'Design for Development' (DfD) is an old concept that finds some of its roots in "Design for the real world" by Victor Papanek and Buckminster Fuller [94]. They argued that industrial design was uniquely positioned to solve the problems faced by the global population. At the time, this was a contrasting view since the purpose of '*design*' was thought to only be for creating, producing and selling industrial goods.

The goal of DfD, on the other hand, is to improve the livelihoods of people in MC [113]. Unlike typical design approaches, DfD proponents suggest focusing on ethics, social justice, livelihood

and sustainable development more than user-centricity [113], [114]. Oosterlaken suggests using 'capability approach' (CA) frameworks for designing solutions for the MC [114].

The CA framework is used to assess and evaluate people's wellbeing, social arrangements, policy, and proposals of social change within a specific context [115]. CA, in essence, suggests that people should have the freedom to choose "the kind of lives they have reason to value." [115]. CA is primarily used in welfare economics and developmental studies, but lately, it is finding more and more mention in the design-related literature [8], [114], [116]. CA is an evaluative rather than a prescriptive framework and is characterised by a focus on "*what people are able to do and to be*" [115]. Thus, CA can be used as a framework for evaluating the impact of a design solution on MC.

Applying the CA practically in design is a challenge due to the contextual nature of the theory. However, some scholars have attempted to meet the challenge by developing supports that let designers better understand social scenarios [117]. These supports are similar to some existing design toolkits, such as the Market creation toolkit and HCD approach [118], [119].

Design for wellbeing (DfW) is another subset of DfD approaches where the focus is on creating socially responsible designs for mitigating injustices and inequalities at the MC [120]. DfW solutions are different from typical design projects since the aim is to create engaging and fulfilling opportunities for the people for their overall happiness [8].

According to DfW and DfD theory [8], [113], [114], for successful design projects in MC, designers should 1) Focus on gaining a deep understanding of users abilities and motivations through empathetic design, 2) Use participatory approaches, 3) Collaborate with organisations and agencies of different backgrounds, 4) Iteratively develop solutions, 5) Try to improve the capabilities of engaged organisations, 5) Design products and services that are easy to use, flexible and accessible, 6) deliver accompanying policies and social interventions along with products and services, and 7) Attend to issues of distribution, repair and end of life in the initial design phases.

A criticism of DfW is that it assumes that consumption of goods and services will somehow result in capability improvement and wellbeing [8]. However, proponents suggest that the DfW and DfD approach help people make choices to better their skills and, thus, their wellbeing [8], [114].

1.4.4 Appropriate Technology

Appropriate Technology (AT) also has similar roots as DfD. It is based on the work of E.F Schumacher, who saw the limitation of western technologies in providing sensible solutions for 'third-world' countries [121]. Typically appropriate technology is understood as intermediate solutions between high end and performant solutions typically available in high-income countries and low-cost rudimentary ones available in low-income countries (e.g. something 'midway between a hand hoe and a tractor') [122]. Schumacher assumed that such intermediate technology would be cheaper and easier to produce than highly sophisticated and capital-intensive technologies suitable for MC [122].

Barring the obvious limitations of such an assumption, Schumacher's recommendation for designing solutions for MC still holds good. Solutions for MC should be made locally, be reproducible in large numbers to reduce costs, production methods should be simple and skill irrelevant, and materials should be locally sourced [121], [122]. The technologies are characterised by low cost, small scale, simplicity in production and maintenance at the local level without much

skill and support from knowledgeable entities [123]. Recent literature on AT mainly concentrates on transferring and disseminating low-cost technology to rural and impoverished contexts [122].

The issue with AT foundations is that it assumes breakthrough technological innovations are unsustainable in the low-cost environment [123]. Recent literature in allied domains has uncovered cases that prove otherwise. For example, The Vestergaard life straw[53] is a standalone, unpowered water filter designed for the poor people living in desolate conditions in Africa. The product used cutting edge and novel technology developed in Europe and has been successfully deployed in the field and disseminated to the people.

The second issue with AT is that there are very few empirically validated methods and methodologies. One attempt at defining a methodology for appropriate technology development is by Ramani et al. [124], who design toilets for the bottom of the pyramid market. Another approach is by Sianipar et al. [125], who present a framework for the engineering design of AT by combining NPD approaches with community involvement and a participatory design framework.

1.4.5 Participatory Design

Participatory design or Co-design is a set of design approaches where users play an active role of social researchers or designers during the creative development process [126]. Users participate as are decision-makers in the analysis, evaluation and implementation of a design solution. In contrast, users are passive members of the process in typical design approaches, and designers merely seek to understand their needs. Participation approaches are operationalised using various collaborative methods and tools such as prompts, probes and visual maps [127], [128].

Co-design and the active participation of the users when designing for MC is essential for creating successful and appropriate solutions and provide several benefits [83]. For example, using tangible technological artefacts during co-creation exercises with users who have limited exposure to technology is helpful for understanding and observing their expectations [129]. Insights and understanding of the MC and people's lives can be done more effectively using participatory methods [83]. Such approaches also empower people to solve their problems creatively and thus enhance their capacity for designerly thinking [130], [131].

However, there still are problems in implementing participatory approaches in MC. the nature of the participatory approach in MC is different from those used in developed contexts [130]. Several issues arise due to social hierarchies, power differences, low literacy and language barriers [83], [132]. When working with people in poverty, their daily inflow of income restricts them from joining participatory workshops [130]. People in MC have hectic schedules, low technical skills and do not necessarily trust outsiders. Therefore, even planning the participatory design exercises must be collaborative activities to mobilise local participation and build trust [130]. Hussain et al. [130] suggest that designers create trust and rapport with the people in MC before organising participatory sessions and adequately compensate them for being part of the activities.

Many authors have attempted to develop frameworks that operationalise the participatory design approach and integrate them into the design process. Moravej et al. [133] and Brandt [134], for example, use methods such as comic book creation and playing collaborative games as a participatory exercise to design solutions. Still, there seem to be some issues that need addressing for implementing participatory approaches in MC.

Overall, participatory design is indeed a promising approach for design in MC. The key recommendation for employing participatory approaches in MC is that designers should immerse themselves in the context by conducting meaningful activities with the people. Therefore, A holistic design methodology for MC must be ingrained with participatory approaches and employ strategies to mitigate the known issues for its effective implementation in MC.

1.5 Discussion on Literature Review

This chapter presented a summary of the extant literature review conducted to understand the foundational topics of Frugal Design. Literature related to poverty economics, marketing, innovation and design approaches were focused on and extensively reviewed. Typical design methodologies were found inadequate for designing solutions for MC since the challenges faced by the people living in poverty are so diverse, complex and interconnected. Based on the outcomes of extant literature, some recommendations for design approaches in the MC could be devised. Some critical constraints that inhibit the design process were also identified through the review. These outcomes are discussed in the sections below.

1.5.1 Recommendations for Frugal Design

Three ‘verticals’ were found around which the overall recommendations for designing holistic solutions for MC were concentrated, these were:

- 1 Product Design: recommendations that pertain to the artefact in the holistic solution.
- 2 Strategic planning and business: Recommendations relating to developing a plan for delivering the value to the final customer.
- 3 Dissemination and Execution: Recommendations relating to executing the design process and distributing context-specific solutions.

A summary of the recommendations organized using the three verticals and product life cycle stages are presented in Table 1.4. Appendix A presents a comprehensive version of this table.

Table 1.4: Consolidated list of recommendations for Designing in MC

Product Lifecycle Stage	Recommendations related to Product Design	Recommendations related to Strategic planning and business	Recommendations related to dissemination and Execution	Key references
Design	Increase the design scope; develop deeper user understanding; ‘de-skill the product; Focus on core function; add multiple functions; Change product architecture; Design products with a larger lifespan.	Consider affordable business models; Reduce total lifecycle cost; Consider PSS model; incorporate local stakeholders into the value chain; Design strategies for scaling up at the early stages	Engage designer till product use stabilizes; Consider a capability approach in impact evaluation; Incorporate local stakeholders to Co-Create; Design income generation opportunities	[3], [7], [30], [35], [68], [96], [107], [135]–[137]

Mfg.	Reduce manufacturing complexity; Use frugal infrastructure; Use standard parts; Design for robustness; reduce maintenance; Reduce errors in manufacturing	Use flexible and scalable manufacturing; Partner with local entities; Manufacture close to context; Consider distributed manufacturing	Use less mechanization and more labour; ally with local inventors and innovators	[96], [137]–[141]
Distribution / Purchase	Design for transportation in large numbers; Consider non-traditional communication design	Package in smaller sizes; Partner with local players dissemination; Consider non-traditional distribution methods such as mobile outlets, Community based distribution etc.;	Consider the long-term impact of consumption; Benchmark product affordability with an existing substitute; Develop a strong brand	[70], [96], [137], [142]
Use	Design for use in extreme and unreliable conditions	Provide financial support for product ownership and maintenance; Collaborate with local financing organizations	Train and educate for effective use; Provide entrepreneurial training to stakeholders; build confidence and trust in the brand; Develop local social networks	[33], [35], [36]
Servicing	Design multiple and low friction services; incorporate services to upgrade, modify and refurbish	Use deferred payments, microfinance, cashless transactions, mobile payments; Consider a pay per use or 'servitized' model post-purchase	Reduce the perceived time and effort for services	[30], [35], [139], [145]
Recovery /Disposal	Design parts for easy retrieval of biological and technical nutrients in local vicinity; Eliminate or minimize parts that may end up in landfills or water bodies	Provide services for update, modification, repair and take back	Device mechanisms to proactively scout for obsolete, broken and unused products	[35], [111], [139], [146]

Insights from the extant literature review help in proposing a clear definition for 'frugal design' as follows:

'Frugal design' is a low-resource consuming design process for developing sustainable and holistic solutions that are available to users at significantly low costs and perform optimally to adequately meet the needs of stakeholders in a design context. The outcomes of such a process can be called frugal design solutions.

Besides the ones mentioned in Table 1.4, some overarching recommendations for a holistic frugal design approach were also identified in the extant review.

The review found that low quality and inferior products originating from a cost-cutting mentality do not work in the MC. Design for MC needs to consider novel product architectures and embody products for robustness and durability. Designers must design unique product architectures that consume low resources in design, development and use to mitigate affordability constraints. Product architecture redesign also helps designers create low-cost solutions if simple working principles, materials and manufacturing methods are considered.

Frugal innovation recommendations suggest that products should be significantly low cost, focus on core functions and perform optimally [59]. In addition, products must be easy to maintain, upgrade, use and produce. Therefore, designers can use available engineering tools at their disposal to achieve such results.

The most critical aspect of Frugal design is a deep understanding of the MC. Designers need to immerse themselves in the MC to understand the people's lives and socio-cultural practices. Participatory approaches are the most suitable for this purpose. Such approaches have the two-fold benefits of getting people involved in the value chain and providing deep knowledge of the context for the designers.

An effective frugal design approach must incorporate a frugal mindset, consider frugal development processes, and deliver a frugal outcome [53]. Participatory approaches and an immersive understanding of the context can build a frugal mindset of designers.

A Frugal Design process must also be executed in close collaboration with various agencies in the MC as well. Designers can engage NGOs, administration, local leaders and other institutional players in co-design activities. Such collaborative activities could also help designers build trust and help in downstream product development. Non-traditional collaborations are also essential for creating an effective value chain.

Typically, organizations face a lack of infrastructure when delivering solutions to the MC. There are also other institutional barriers to dissemination. Such barriers can be circumvented by collaborating with agencies in the MC, such as NGOs and administration, to understand the needs of the context, develop the solutions, and build a sustainable network for distributing it. Organizations can also collaborate with MSME industries for prototyping and developing the solution. Such local collaboration can also potentially improve sustainability by employing local manufacturing, material and resources for development.

One of the major issues identified for solutions in MC is their dissemination and delivery. Besides business strategies that can help mitigate such issues, designers must also develop unique strategies for creating awareness. Designers can strategically leverage social networks in MC to support the dissemination and deployment of solutions.

Solutions for MC need to be affordable, which may be challenging when employing high technology processes. It is the responsibility of designers to develop novel system architectures to circumvent such affordability constraints by implementing methods such as PSS and pay per use business models. However, despite the potential affordability of PSS solutions, any solution that needs constant payments from users may become a burden for the people. Therefore, a frugal design approach must have checks and balances to ensure solutions that do not burden people's sustenance.

It is essential to develop scalable businesses and socio-technical solutions for MC. However, when businesses serve a large population, they may negatively offset any sustainability benefits of a frugal solution due to the 'rebound effect' [75]. The frugal design thus must critically consider the end of life scenarios and other PLC stages of the product. A holistic design should provide appropriate services for managing the end of life scenario and have systems that cater to such needs.

Furthermore, the evaluation of the impact of Frugal solutions should be incorporated into the design process. The evaluation must be done on broad agendas rather than product performance and sale. A frugal design approach can use frameworks like the capability approach to assess the improvement of the wellbeing of users. Solutions should also be evaluated based on their life cycle, long term impact on the MC and sustainability parameters.

Overall the approach for Frugal design must be iterative that considers product design, service design and strategic design, and interdependencies in implementing them. It should integrate deep user and context understanding, Product design methodologies, Novel strategies for service and business, and methods for effective dissemination of solutions in the MC.

1.6 Research Gaps and Questions

Several research gaps were identified from the extant literature review. Firstly, the lack of a holistic and systematic framework for frugal design in MC was evident. Although some design frameworks were identified [119], [137], [147], they also lacked in crucial ways.

Mattson and Wood[137] provide a generic strategy for solution finding and a list of recommendations for organizations in developing solutions for the BoP. However, the model is heuristic and provides little clues on implementing the framework practically. Similarly, Jagtap & Kandahar's [119] model is focused on the effect of a solution on MC but does not provide details of implementing it in the context. Jagtap & Larssons [30] present a framework for designing PSS models for MC, but it does not detail the product design aspects.

The most comprehensive model of a design approach identified was given by Castillo, Diehl & Brezet [147]. The model considers design activities ranging from distribution, marketing and communication to monitoring and suggests using co-creative and strategic design activities to support the solution. In addition, the authors suggest relevant design tools that can be used with the framework. Unfortunately, follow-up research of its use in projects or evidence for its empirical validation could not be identified.

Many proposed design approaches in MC have a similar shortcoming due to a lack of theory-driven research and empirical validation [119]. In theory-driven approaches, a theoretical construct is first developed and then tested using empirical data. Moreover, a significant part of the existing research is related to the front end of the design process [148]. Very few frameworks focus on the latter development and holistic strategic aspects of Frugal designs.

Another gap is the lack of specific tools and design supports for designing for MC. Some tools have been reported [146], but these are limited to the user understanding phase. Most frameworks suggest using existing tools for the purpose [147], but these need to be significantly modified for

the MC. Additionally, there are very few tools for supporting participatory approaches and holistic design in MC.

A Frugal mindset has been suggested as a key component for developing frugal solutions in MC [53], [149]. Typically, a mindset is not considered within the scope of any design approach. However, identifying novel ways of using a limited resource for development is a crucial facet of *designerly* thinking when developing frugal solutions. Therefore, an effective approach needs to imbibe a frugal mindset is necessary. Unfortunately, the 'Frugal Mindset' phenomenon is not clearly understood, nor are there specific strategies for imbibe it. Literature suggests that the effectiveness of a frugal design approach depends on the frugal mindset [53].

Finally, specific methodologies or approaches for evaluating design concepts in marginal contexts could not be found. Selecting design concepts in MC is difficult to the cumulative effects of socio-technical constraints on the design solution. It is difficult to simply gauge the effectiveness of a solution in MC by evaluating product performance parameters [86]. Therefore, an effective means of evaluating design concepts in early phases will benefit frugal design.

In summary, the following research gaps were identified after extant literature review:

- 1 There is a lack of design frameworks and approaches for systematically generating holistic and frugal product design solutions for marginal contexts.
- 2 The few design frameworks which exist have not been empirically evaluated.
- 3 There is a lack of specific design strategies that practitioners can easily implement in their projects.
- 4 There is a lack of design tools and supports for frugal design in general. In addition, tools that support participatory approaches and holistic design are rarer. Most design tools are focused on the front end of the design. Latter development stages have no specific tools for Frugal design in MC.
- 5 There is no clear understanding of the Frugal mindset phenomenon. Moreover, specific tools, strategies and approaches for imbibe a frugal mindset could not be found, despite the phenomenon being considered essential for design.
- 6 There are no specific strategies, approaches or tools for evaluating and selecting frugal design concepts in early design phases.

1.6.1 Research Questions

Based on these research gaps, two research questions were formulated for examination in this thesis.

- 1 Research Question 1: What will be an effective approach for designing frugal and holistic solutions for marginal context?
- 2 Research Question 2: What will be an appropriate design tool to support a systematic frugal design approach throughout its implementation?

The objectives for the above research questions were formulated based on the uncovered research gaps.

1.6.2 Aim and Objectives

This research project aims to develop a framework for the systematic design of frugal and holistic product concepts and implement it through a design tool.

The following objectives were formulated to meet the aim, fulfil the research gaps and answer the research question in the process:

- Objective 1: To identify the recommendations for designing frugal and holistic products for marginal context
- Objective 2: To identify the important design strategies needed for implementing frugal and holistic solutions for marginal contexts.
- Objective 3: To understand the challenges and constraints in implementing the design recommendations and strategies when developing product concepts for marginal contexts.
- Objective 4: To develop frameworks for the systematic conceptualisation and evaluation of frugal and holistic design concepts that implement various recommendations identified.
- Objective 5: To verify the effectiveness of the systematic conceptualisation framework using an empirical approach
- Objective 6: To understand the phenomenon of 'Frugal Mindset' and identify strategies for implementing it.
- Objective 7: To implement the framework for systematic conceptualization as a design tool.

1.7 Research Plan

The objectives led to the detailed planning of this research and defining the specific studies necessary to answer the research questions adequately. Table 1.5 summarises the research plan and shows the various studies done in this research project with a short justification for each.

Table 1.5: Summary of the research plan and the studies with their short justification.

Objectives	Studies Planned	Justification for the chosen Study
Objective 1: To identify the recommendations for frugal design	Study 1: Literature Review	An extant literature review related to design in marginal contexts within multiple domains is necessary for a holistic understanding of frugal design and identifying the design recommendations.
Objective 2: To identify the important design strategies	Study 2: Analysis of Existing case examples	Analysing existing case examples and their characteristics can help understand key strategies employed when designing products of different types and with different focuses. Contrasting such strategies between successful and failed cases can uncover the design strategies indispensable for frugal design.
Objective 3: To understand the challenges and constraints in frugal design	Study 3: Analysis of Product Design Experience	A practical understanding of challenges and constraints in designing appropriate solutions for MC needs an immersive experience in the field. Such an experience can help uncover specific requirements for an effective frugal design process.
Objective 4: To develop frameworks for conceptualisation and evaluation of frugal design	Done through the synthesis of research outcomes.	The research aims to develop a systematic approach for designing holistic and frugal solutions for MC. Therefore, the research outcomes are synthesized to develop a relevant framework.
Objective 5: To empirically verify the effectiveness of the systematic frameworks	Study 4: Empirical Evaluation of a Systematic Design Framework:	There are very few empirically validated design approaches for developing holistic solutions for MC. Empirical evaluation provides robust insights into the practical effectiveness of research outcomes in design.
Objective 6: To understand the 'Frugal Mindset.'	Study 5: Understanding Frugal Mindset	Understanding the frugal mindset phenomenon is essential for creating frugal products. Specific strategies for imbibing its characteristics are needed to effectively implement the frugal design process.
Objective 7: To develop a design tool.	Study 6: Development of a toolkit for Frugal Design and its preliminary evaluation	Developing design supports is essential for translating the research findings into practically applicable methods and is a recommended process in Design research [1]

The various studies conducted in this thesis are described below:

- 1 Study 1 –Literature Review: This chapter presented the extant literature review to understand the insights and foundations of frugal design. This study also helped to identify the research gaps for the project.
- 2 Study 2 – Analysing Existing Case examples: This study aimed to fulfil the **second objective**. It was unclear from the review which design guidelines need more focus when designing products of different complexities. A qualitative case study analysis of existing solutions was done to identify the relative importance of design guidelines and strategies. This analysis provided an understanding of critical focus areas when designing certain product types
- 3 Study 3 – Analysis of Product Design Experience: A researcher needs to don the practitioner's hat to fully appreciate the applicability of theories and supports developed. A retrospective analysis of projects was conducted to gain the deepest possible understanding of frugal design and fully appreciate the challenges and constraints when designing for MC. The analysis identified key design constraints in MC and a set of requirements for a systematic frugal design approach.
- 4 Study 4 – Empirical Evaluation of a Systematic Design Framework: The research outcomes and insights were synthesised into a framework for a frugal design approach to meet **objective 4**. it was important to evaluate the proposed frameworks to fill the research gaps identified and meet **objective 5**. An experimental study was conducted, which clarified the effectiveness of the synthesised frameworks and clarified their implementation into design supports.
- 5 Study 5 – Understanding Frugal Mindset: The research gaps presented that frugal Mindset was one of the key pillars of a frugal design approach, albeit one that is not clearly understood. This study focused on identifying specific strategies to imbibe such a mindset using a qualitative methodology. Analysis of interviews with several expert designers highlighted their motivations, strategies for identifying new design opportunities and a clear idea of 'frugal mindset'.
- 6 Study 6: Development of a toolkit for Frugal Design: This study operationalized the research findings into a practical tool for designers. A design process was followed to develop a novel toolkit for supporting systematic frugal design. A preliminary evaluation of the toolkit was done to understand its usability. Outcomes highlighted the toolkits effectiveness and directions for future development.

Following the methodological framework in 'DRM- A Design Research Methodology' [1], The research project can be called a 'Type 3' Project as illustrated in the table below:

Table 1.6: Research Plan and its alignment with the methodological framework in DRM - A Design Research Methodology [1, p. 16].

DRM Stages	Objectives of DRM stages	Type 3 Design Research Project activities	Alignment of studies Undertaken in Thesis with Type 3 Design research project as per DRM
Research Clarification	To formulate worthwhile research goals	Review Based Research Clarification	Study 1: Foundational Literature Review

Descriptive Study 1	To develop a detailed understanding of the phenomenon.	Review Based Descriptive study	Study 2: Analysis of Existing case examples Study 3: Analysis of Product Design Experience Synthesis of design frameworks for frugal design Study 4: Understanding Frugal Mindset
Prescriptive Study	To elaborate the initial understanding and design support development	Comprehensive Prescriptive Study	Study 5: Empirical Evaluation of a Systematic Design Framework Study 6: Development of a toolkit for Frugal Design
Descriptive Study 2	To understand the impact of design supports	Initial Descriptive Study 2	Study 6.1: Initial evaluation of the toolkit

1.7.1 Thesis Structure and Flow

The research project followed the structure shown in Figure 1.5, highlighting the various studies undertaken, how each one added to the thesis outcomes and where they can be found in upcoming chapters. References to the chapters are provided at the end of each one for easier access.

This first chapter presented the foundational topics related to frugal design. The key outcomes were the understanding of the MC and the recommendations for designing frugal and holistic solutions for MC.

The second and the third chapters help develop a deeper understanding of frugal design through case study analysis. The second chapter presents Study 2, where prominent cases of successful and failed solutions for MC were analysed to understand the focus areas for developing different types of products in MC. The third chapter presents a retrospective analysis of four design projects. The analysis highlighted the challenges and constraints for designing in MC and helped define the requirements for a systematic Frugal Design approach.

The fourth and fifth chapters are similarly linked. A set of novel frameworks synthesising prior research outcomes is presented in chapter four, whose experimental evaluation is discussed in the fifth chapter. The fourth chapter also reviews exiting design methodologies to synthesise frameworks for systematic frugal design in MC. The fifth chapter presents a novel methodological approach for empirical evaluation of the synthesised frameworks using subjective multi-criteria decision-making methods.

The sixth chapter focuses on understanding the 'frugal mindset' and presents a framework for its understanding based on Study 5. The chapter also discusses the unique motivations of designers working in MC.

The seventh chapter describes the process and outcomes of designing and evaluating a toolkit that operationalises the insights gathered in this research. The final chapter provides a short conclusion and overview of the key research outcomes, philosophical standings and future scope of the research presented in this thesis.

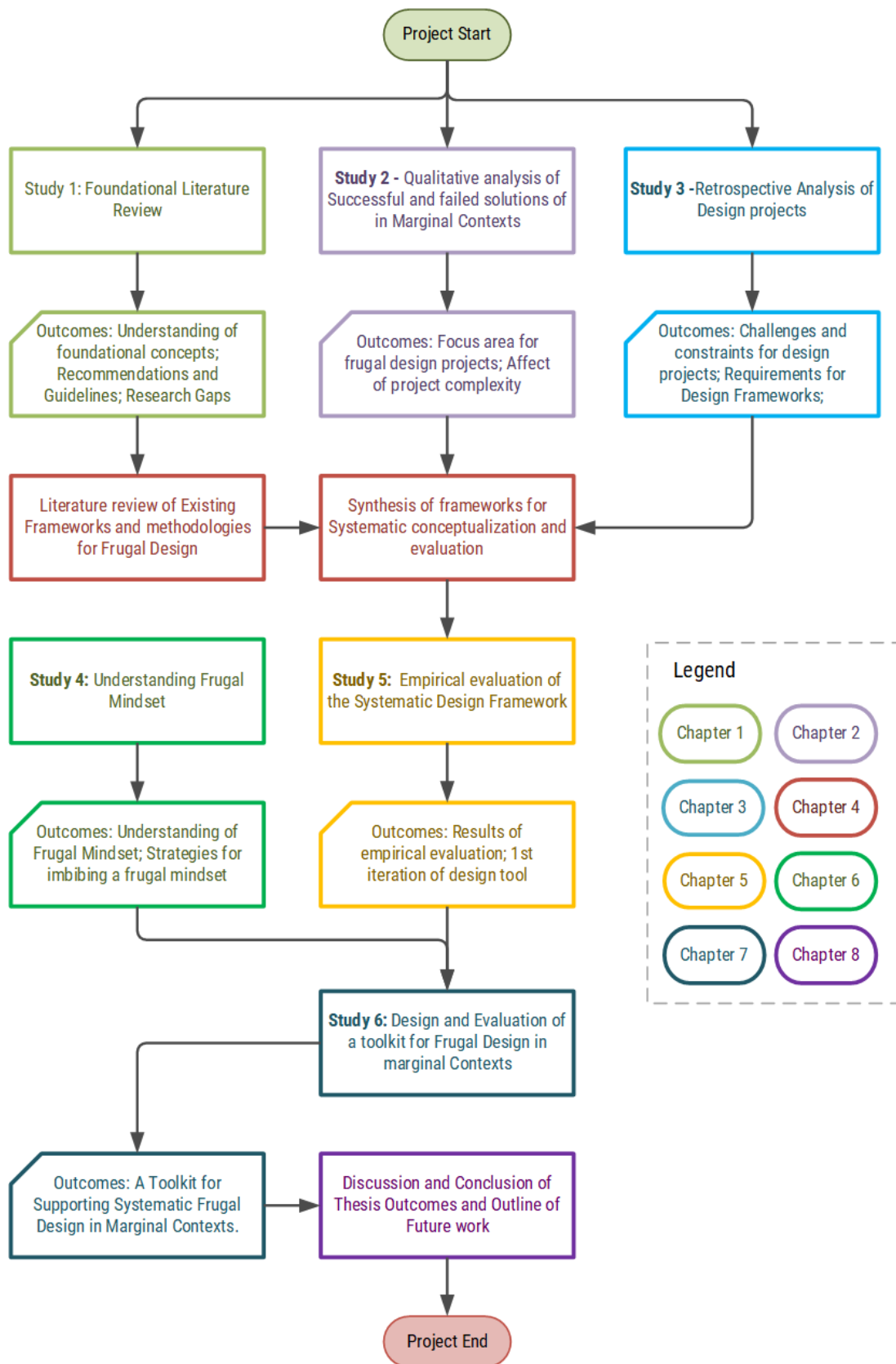


Figure 1.5: Overview of Thesis Structure

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Chapter 2 Analysing Existing Design Solutions in MC

This chapter discusses the outcomes of a case study analysis to better understand the design, development, and dissemination of frugal solutions in marginal contexts (MC). The analysis highlighted that certain design aspects need more focus depending on the project's complexity and characteristics.

Additionally, design guidelines in the literature were relatively abstract since they did not specify how they could be implemented in practice. Designers must know specific ways to practically implement such guidelines for an effective frugal design approach. One outcome of this study was identifying strategies in which the key design guidelines can be practically implemented.

The Study outcomes emphasise that successful products in MC are not simply artefacts but holistic solutions. Also, successful frugal design in MC requires integrating creative design, rethinking production practices, reconfiguring value chains, novel business models, and a frugal mindset. Although it may be difficult to predict the success of a solution during its development, it is argued that a systematic approach to frugal design can undoubtedly increase its chances.

The chapter is divided into two parts, 1) Analysis of Notable Case examples and 2) Analysis of Failed Case Examples. In the first part, prolific solutions for MC are analysed to understand the 'focus areas' of frugal design for different product types. In the second part, some notable failed cases are analysed to understand the critical design guidelines that must be implemented. This analysis provides a list of critical design guidelines and some strategies to apply them practically.

2.1 Rational for Case Study Analysis

Designing, developing and distributing solutions for MC has been studied from perspectives such as Product design [1], Strategic design [2], Sustainable development [3], and Supply chain management [4]. Case study analysis is a commonly used methodology in such related literature to understand the antecedents and guidelines for developing solutions in MC [2], [5], [6]. In this study, a two-part case analysis was considered for qualitatively understanding the significance of existing recommendations and guidelines to a frugal design process.

Although the guidelines and strategies identified in the extant literature review were exhaustive, their relative practical importance in a frugal design process was unclear. This lack of specificity makes it difficult for practitioners to implement these guidelines easily. The prescriptions are broad and generalised without considering the characteristics and constraints in a specific MC or the types of solution to be designed (e.g. Jagtap 2019 [7]). There is no delineation between recommendations that need more attention than others. Also, Since project complexity and constraints significantly affect a design project [8], certain recommendations may be more important than others depending on specific MCs, project complexities, and solution characteristics.

The strategies, recommendations and guidelines that need more consideration depending on solution types, usage patterns, and specific MC can be called 'focus areas' of a frugal design process. Analysing the strategies highlighted for the success or failure of existing case examples could potentially explain such key recommendations and focus areas.

The first part of the study analysed the design strategies employed by some solutions in MC that have reached a sizable population and are considered successful by most reports that discuss them. A typology based on technology used and how the solutions served the population was used for identifying and selecting the cases. Cases were considered successful also because several authors agreed that they had created a lasting impact on the community they serve and on the topic of frugal design. Due to this impact and subsequent reporting, ample literature and information are available on their development process. The selected cases are analysed from product design, strategic design, services and dissemination perspectives. The analysis highlights how each of the cases leveraged the unique characteristics and constraints in the MC and discusses the focus areas for frugal design needed for developing different types of solutions.

The second part presents a unique study of unsuccessful solutions. Not all solutions designed for the MC are successful. Unfortunately, failed solutions are typically not reported in the media or academic literature. However, valuable learning can be derived from analysing such solutions. Section 2.3 presents the findings of a systematic search of failed case examples and their analysis based on the state-of-art design guidelines. The critical design guidelines for designers to implement during a frugal design process are identified and discussed.

2.2 Analysing Notable Solutions in MC

A simple search can uncover many cases examples of product designs for MC. Many of these fit the three criteria of frugal innovations given by Weyrauch and Herstatt [9]. i.e. 1) Frugal solutions are significantly low cost than existing solutions, 2) They focus on a core functionality, 3) They are optimised to perform well in the core functionality. The 'engineering4change' database¹ and 'Siemens - empowering people network'² list hundreds of product design solutions for MC. However, some solutions have had more popular and academic literature coverage than others. Analysis of a sample of such prominent cases was considered for this study. A grid with the social grouping and technology fidelity was constructed to select a fair diversity of cases, as seen in Table 2.1. The four quadrants show four different types of design solutions for MC.

Table 2.1: A typology of Solutions considering use and technology fidelity

	Individual Use	Group use
High tech	These products incorporate high-end technology and are designed primarily for individual or household use: e.g. Tata Nano, One Laptop per Child XO. Gravity Light, D'Light Solar Lantern, Vestergaard's LifeStraw	These products incorporate high-end technologies and are primarily designed to be used by a user group such as a community, locality, village etc. e.g. Piramal Sarvajal water filters, Vortex Grammateller ATM, GE ECG machine

¹ www.engineeringforchange.org

² www.empowering-people-network.siemens-stiftung.org

Low tech	These Products employ simple working principles and construction and are primarily designed for use individuals or households, e.g. Mitticool Fridge, Nilkamal Wello water wheel;	These products employ simple working principles and construction and are primarily designed for user groups such as communities, localities, and villages. E.g. Play pumps, Community housing projects; IDE Treadle Pump
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A few of the frugal design case examples from each of the four quadrants in Table 2.1 were selected for analysis. The selection was based on accessibility to multiple literature sources related to the design of these case examples.

2.2.1 Methodology for Analysing Notable Cases

A literature search and general web search helped identify highly regarded case examples that multiple outlets had widely reported. Additionally, there have been many academic reports where multiple case examples for solutions for MC have been discussed [10]–[13]. These reports were analysed, and the case examples that overlapped with our searches were assumed to represent the most notable and successful solutions.

After selecting cases, Relevant literature to understand the design, development, and dissemination of these solutions was identified. For ensuring an accurate understanding of the cases, an extensive literature search was done in academic databases (Scopus and Google Scholar) and web search engines, using keywords such as ‘design process’, ‘development process’, ‘marketing and distribution’, combined with the names of the cases. The literature gathered was reviewed and catalogued for conducting the analysis.

Next, the selected literature was extensively read, and specific strategies used for product design, strategic design, service design and dissemination of the solutions were noted. This part of the analysis was investigative, where the researcher searched for evidence of specific strategies and organised them into groups. In the next step of the analysis, the strategies were interpreted to find the focus areas needed for each category in Table 2.1.

The following sections briefly discuss each category of solutions and the key strategies for product design, strategic design, service design and dissemination. Section 2.2.4 presents the ‘focus areas’ for a frugal design process relevant to each solution category.

2.2.2 High Tech – Individual Serving Solutions

Although frugal innovation’s origins were in low cost and grassroots solutions, many recent solutions have leveraged cutting and science and technology to deliver low-cost, optimised and highly performant [12], precisely in the manner suggested by Weyrauch and Herstatt [9]. Furthermore, Rao [12] suggests that frugal solutions that implement high-end technology solve conflicting requirements to achieve novelty. For example, the Vortex Grammateller ATMs are designed explicitly for MC and perform at par with existing products despite an unreliable electricity supply, high temperature and humidity conditions and absence of air conditioning [14]. Similarly, One Laptops Per Child’s XO laptop designer balanced the conflicting constraints of having beautiful materials and finishes for the product with low cost and scalable manufacturing methods [15], [16].

Individual serving solutions are typically designed for extensive use by a single person or household. Examples of such solutions include the Tata Nano, OLPC's XO Laptop, Deciwatt's Gravity Light, D'Light's Solar Lanterns and Vestergaard's LifeStraw water filter.



Figure 2.1: Tata Nano is considered the epitome of Frugal Engineering [72]. It is highlighted as the \$3000 car in popular marketing. Image: Tata Nano, Image Source: Wikimedia Commons



Figure 2.2: OLPC XO Laptop. One Laptop Per Child makes robust and unique laptops marketed as the \$100 laptop[16]. Image Source: Wikimedia Commons



Figure 2.3: Deciwatt Gravity Light®. Deciwatt used to make an LED light, where a falling weight was used to light up an LED. Image Source: engineering 4 Change Database [14]



Figure 2.4: D'Light S30 Solar Lantern. D'Light makes many solar lighting solutions typically targeted towards off-grid and MC usage [15]. Image Source: D'Light Website [16]



Figure 2.5: A lady using the LifeStraw®. Vestergaard's LifeStraw® is a personal water filter that uses a cutting-edge filtration system in a portable package, marketed towards MC and off-grid context [17]. Image Source: NYTimes [18]

Three cases were selected for understanding the design strategies employed by high tech and individual use product design solutions. The Tata Nano car is a unique case because it was considered a pivotal example of frugal engineering and innovation[17] but failed in the market [18]. Still, it is one of the most documented case examples that enable a check of the employed strategies.

Tata Nano was the brainchild of CEO Ratan Tata, who was inspired to create the car after seeing a family of four using a scooter as primary means of transport. He assembled a team of young engineers to create a 'one lakh rupees' car in close collaboration with existing suppliers and OEMs [19]. Some of the unique strategies used by Tata Nano are highlighted in Table 2.2.

Vestergaard's LifeStraw® is another case example that has been extensively covered in the media and literature [20]. The product started as a research exercise to design a mesh filter to remove

guinea worms from potable water. Since then, the technology was updated to enhance its filtration capability, which later on was used in the LifeStraw product [21]. The company has also incorporated the technology into myriad products for various use cases.

Similarly, D'Light started as a startup by a few Stanford University graduates who wanted to design lighting products for the MC [22] and replace the ever-present kerosene lamp [23]. The company was funded through social business venture funds and has since grown to operate in multiple geographies [24]. Table 2.2 summarises the different strategies employed by the selected cases.

Table 2.2: Summary of the design strategies used by notable high-tech individual-serving case examples.

	Tata Nano	Vestergaard LifeStraw	D'Light
Product Design	<p>Considered significant <u>product architecture</u> changes to reduce the product costs.[25]</p> <p>The existing embodiment of several <u>critical components</u> was <u>overhauled</u> to reduce cost.[19]</p> <p>Collaborators and Suppliers were trained and onboarded to the <u>frugal engineering philosophy</u> [17].</p>	<p><u>Multiple versions</u> were designed using the technology to cater to multiple use cases [26].</p> <p><u>Stringent standards</u> for performance testing were used. [27], [28]</p>	<p>An ecosystem of products was designed, including <u>product variations</u> for different use cases [29].</p> <p>Followed <u>iterative prototyping</u> and design-thinking based approach for developing initial products [29].</p>
Business and Strategic design	<p><u>Non-Traditional Benchmarks</u> were used. For example, The high-end two-wheelers used by the Indian population was considered as the main competition [25].</p> <p>The materials, parts and components were <u>sourced from a select set of local and exiting suppliers</u> in the value chain [17] [19].</p> <p><u>Unique use cases</u> were considered. E.g. it was sold to institutional buyers internationally for use as taxis [19].</p>	<p>Followed a unique <u>humanitarian for-profit</u> business model [30].</p> <p><u>Grants and supplemental funding</u> were used to offset the high product cost when selling to MC. [31].</p> <p>Used <u>carbon offsetting</u> methodologies as well as other environmental certification programmes. [32].</p>	<p><u>Microfinancing schemes</u> were utilised to make larger product systems affordable for the masses [33].</p> <p>Employed <u>carbon credits</u> based methods for offsetting environmental effects [33].</p>
Service Design	<p>A <u>unique consumer experience</u> relevant to target buyers was devised, e.g. Salesforce was trained to reduce the intimidation felt by rural buyers [34].</p>	<p>Used <u>household level sensitisation</u> programs to help solve problems and identify solutions [35].</p>	<p>Provided <u>services for product upkeep</u> in use and during the payment time [36].</p> <p>Provides <u>access to additional products</u> such as FM radios to support the product ecosystem [36]</p>

<p>Dissemination and Distribution</p>	<p><u>New distributor networks</u> in tier two cities were set up rather than marketing in metros [17].</p> <p><u>Specific training</u> was provided to the distributor network to support new channels [19].</p>	<p>Implemented <u>unique social programs</u> to provide free products to community members based on purchases [32].</p> <p><u>Trained local teams</u> to implement social programs in indirectly related contexts, such as Schools [32]</p>	<p>Focused on <u>measuring product impact</u> through defined metrics for sustainable development and wellbeing [37].</p>
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The analysis highlights some of the interesting strategies suggested in many recommendations. Product design of fugal solutions for MC needs significant architectural changes focusing on developing novel embodiments from the ground up rather than stripping away existing solutions. Creating multiple versions of the solution that helps fulfil multiple use cases is an interesting product design strategy for individual serving solutions. Having a technology platform further enhances the possibility of creating such versions. Successful products employ subsidisation methods and append their cash flow through additional funding even when their costs are high. Pay-per-use and microfinancing solutions seem to improve their affordability further. Many successful cases employ methods to offset carbon impact and offer carbon credits schemes. Such strategies help to gain funding and provide a good metric for measuring the impact of the final solution.

2.2.3 High tech – Group Serving Solutions

When it comes to high technology and group serving solutions, the challenges include providing a sense of product ownership, sensitisation and creating robust solutions. For example, Piramal Sarvajal produces water filters for community use [38]. They implement high tech solutions such as cloud-based monitoring and data capture. However, they must carefully consider the context’s affordability, literacy, and socio-cultural norms. A product-service system model is used along with smart cards and other system-level support to make the product easily accessible for the users [39].

Some notable examples of solutions that serve communities and groups are Piramal Sarvajal water filters, Vortex Grammateller ATM, GE Mac 400 ECG machine (See Figures below).



Figure 2.6: Children using a community water filter (Water ATM) by Sarvajal. Image source: UN global Compact [38]



Figure 2.7: Vortex Grammateller ATM. The product is solar powered and specifically designed for use in rural and uncertain conditions. Image Source: Vortex Engineering



Figure 2.8: A technician using the GE Mac 400 Portable ECG machine in a rural dispensary. Image source: Forbes India [42]

General Electric’s first foray into the frugal innovation domain started with the Mac 400 ECG [40]. The product is a low-cost machine designed from the ground up for the Indian markets where the costs of a typical ECG machine proved to be too prohibitive for the rural and middle-income healthcare sector [41]. The machine used off the shelf components, such as a bus ticket printer, to circumvent expensive modules in the machine [42]. After its immense success, the product was then launched in international markets. This case example also gave rise to the concept of reverse innovation [40]. The product’s success enabled GE to seriously consider developing custom products for the emerging markets, which they followed with the development of low-cost X-Ray machines and baby warmers [42].

Piramal Sarvajal makes water filter for community use in rural and semi-urban India. It started as a CSR venture of the Piramal Group that evolved into a thriving solution for the MC [38]. The solution was a cloud monitored smart card activated water filter for communities lacking potable water [39]. The device works on a PSS model where users pay for the filtered water, and the company owns and maintains the device at their cost [43].

Vortex Engineering is an Indian company that makes ATMs for marginal and rural contexts. It started as an incubated project in IIT Madras, focusing on developing a solution that worked in rural India’s harsh and unpredictable environments [44]. The Grammateller ATM is engineered to produce less heat in operation, thus not requiring air conditioning. It works on solar and consumes 10% of the energy consumed by its competitors. The product design incorporates the usual functionalities in ATMs and solves problems typical to the Indian MC, such as the reliable handling of soiled notes [45]. Table 2.3 summarises the analysis of the cases with specific strategies employed by each.

Table 2.3: Summary of the design strategies used by notable high-tech group-serving case examples.

	Piramal Sarvajal	GE ECG machine	Vortex Grammateller ATM
Product Design	<p><u>Used solar power</u> to lower the dependency on the grid. [39]</p> <p><u>Used cloud-based monitoring</u> of individual products to track usage and provide effective maintenance.[39]</p> <p>Provided <u>onsite troubleshooting</u> by local people using proprietary devices[39]</p>	<p><u>Off the shelf and low-cost components</u> were used to replace costly components. [14], [41]</p> <p>The design was <u>battery-operated, lightweight, portable and robust</u> to environmental variations [46]</p>	<p>Designed to use less than 10% energy than competing products by <u>employing Solar power</u> to supplement the grid [44], [47].</p> <p>Designed to generate less heat, <u>work in harsh environments</u>, work with soiled currency [44]</p>

Business and Strategic design	A <u>product-service systems model</u> is used, and the people pay for the filtered water while the company owns the product [43].	Product was <u>improved for selling in developed countries</u> while keeping the aspects that made it frugal [48] <u>Collaborated with banks</u> to provide financial services [42]. The cost of the product was considered based on service. I.e. the product was low-cost per scan [46]	Provides a <u>customised solution</u> with modular components to meet specific customer needs [44]. Operations are <u>appended with support</u> from United Nations and World Bank funding [44].
Service Design	<u>Multiple options for availing of the service</u> are used, including pre-paid smart cards [49]	The company <u>partnered with other multinational companies</u> and even competitors for providing financial services.[42]	The design provides <u>alternate means</u> of authentication using fingerprint [50]. Provides <u>additional services</u> and software to customers for managing the ATMs[45]
Dissemination and Distribution	<u>Local people are trained</u> and provided micro-entrepreneurship opportunities through franchisee operations [39] Uses <u>local level marketing</u> drives in collaboration with schools and hospitals, apart from door to door marketing[49]	Followed a <u>direct sales route</u> by pharma industry sales agents, which was highly atypical for the company at the time [41].	Collaborated with nationalised banks, rural banks and governmental agencies for deployment.[45]

Monitoring, maintenance and assessment become primary design drivers for high-tech products that need to work for the community. Since, in most cases, the product is unsupervised in usage, designers have to consider the user's lack of knowledge and the uncertain environmental conditions. Such high-tech community-serving solutions are typically expensive, prohibiting users or small businesses from owning them. In this case, PSS business models and supplemental funding provide them with better access to the MC customers. As with other types of solutions, collaborative design, business and deployment are essential for such products. Moreover, it is much easier to include local people into the value chain with such products. However, training programs and other supports are needed for the local population to disseminate and monitor the product effectively.

2.2.4 Low tech – Individual Serving Solutions

Grassroots innovation can typically be clubbed into Low-tech Individual-Serving solutions. For example, Mitticool was an innovation by a grassroots entrepreneur who developed a 'refrigerator' using terracotta and the principle of evaporative cooling [51]. Since its recognition as a Grassroots innovation, the innovator has formalised the company and now serves multiple customers with various products, extensively employing terracotta as the base material [52]. However, there are several examples where **organisations** have created low-tech individual-serving solutions that

continue to help people in MC, especially those with extremely low incomes. Three such cases are discussed here (Figures 2.9-11).



Figure 2.9: An Indian woman pushing the Wello Water Wheel.
Image source: engineering4change.org [55]



Figure 2.10: A man pouring water into the Mitticool Terracotta Fridge. Evaporative cooling produces enough temperature difference to store fruits and vegetables for a longer duration.
Image Source: Mitticool [109]



Figure 2.11: A man using the IDE Treadle Pump with Bamboo foot pedals.
Image source: engineering4change.org [57]

Low tech solutions are uniquely positioned for use in extreme poverty scenarios. Moreover, such solutions can also be easily produced with more or less simple manufacturing methods. However, the challenges for such products lie in their scalability and meeting people’s aspirations. For example, for Mitticool, newer target customers are low- and middle-income groups in rural and semi-urban areas. Therefore, they rely heavily on word of mouth marketing and distribution through local shops in the vicinity while supplementing their efforts through online and traditional marketing approaches [53].

On the other hand, low-cost individual-serving products are much easier to be supported through philanthropic and CSR activities. For example, the Nilkamal Wello water wheel primarily relies on its established supply network for distribution but collaborates with local NGOs and governmental agencies to increase product awareness and acceptance [54]. Table 2.4 summarises the strategies followed by the selected cases in this category.

Table 2.4: Summary of the design strategies used by notable low-tech individual-serving case examples.

	Wello Water Wheel	Mitticool Products	IDE Treadle water pump
Product Design	Product Design is simple and uses a rotomoulding process to produce the rolling drum with a bent mild steel Handle [55].	Products are made using low-temperature fired ceramics (terracotta). The company provides many types of products, including utensils and water filters made of terracotta [56]	Product design uses simple construction. Product is suitable for low head operations [57] Product designs are optimised for easy manufacturing and performing in harsh conditions [58].

Business and Strategic design	Product sale and dissemination is <u>funded through philanthropic and sustainability ventures</u> [59] Product is <u>used as an advertisement space</u> for interested agencies [60].	Products are sold to consumers for profit through <u>traditional outlets</u> and web channels [56].	<u>Local manufacturers were supported</u> to develop the product using rudimentary manufacturing methods [58]. Product <u>Renting, multiple ownership, community credit</u> , and microfinance were used to sell [58].
Service Design	The company provides <u>basic maintenance services</u> through its distributor networks [55]	The company provides <u>basic maintenance services</u> for its products [56].	<u>Local people were trained</u> to provide service and technical support for the product [58].
Dissemination and Distribution	The company <u>partners with NGOs, governmental organisations</u> and other agencies for distribution [55]. The company provides <u>support to local entrepreneurs</u> and distributors for selling the product through their business model [54] Rigorous impact and livelihood improvement are <u>measured</u> [54].	Products are sold through online channels, distributor networks and <u>franchisees</u> [56]. Besides traditional routes, products are <u>sold in larger quantities</u> through stalls in prominent exhibitions [61]. Uses <u>women workforce</u> for distribution[62] The company supports local children for their schooling [62].	<u>Local Manufacturing facilities</u> were set up to manufacture pumps [58]. Novel and <u>non-traditional means of advertising</u> were employed, such as calendars, cinema slides, T-shirts and community plays [58], [63].

Analysis of low-cost Individual serving cases suggests a focus on optimising concepts to use simple construction and manufacturing processes while keeping robust performance in key requirements. Business models for such products also follow similar dependence strategies on microfinance and PSS models. The design focus for services was on providing basic maintenance and troubleshooting only. Like other solutions, a strong focus is on collaborating with various local agencies and forming non-traditional partnerships to provide financial and dissemination supports. Such solutions also focus on helping the local population in entrepreneurship and income generation opportunities. Finally, the low-cost solutions use unique marketing and advertising methods when their target population is in low-income contexts.

2.2.5 Low Tech - Group Serving Solutions

Very few highly reported and reviewed case examples were found in the low-tech-group-serving category. This lack may be because it is much easier to develop individualised low-cost solutions than tackling the strategic complexities of group-serving ones. Two of the most famous examples are the Playpumps roundabout and the Sulabh flush compost toilet. Of these, the Playpumps roundabout failed to meet user requirements and impact the MC, due to which it was discontinued.

The benefit of the low-tech group serving solutions is that they are easy to scale, modify and implement in varied MCs. Where individual solutions need to consider the aspirations of the users,

the group serving solutions only need to be functional and focus on performance. Despite their simple design, low-cost materials and manufacturing methods, solutions also need to be robust to unintended uses, vandalism, and harsh environmental conditions. These solutions can also be easily manufactured and produced in large numbers, thus supporting local employment.

The challenges for such types of solutions are in developing service models, business plans and dissemination strategies. Due to the group-serving nature, such solutions cannot be typically marketed and distributed. They need financing support for initial installations, thus creating dependencies on grants and financial aids. Furthermore, novel business models must be created to ensure economic sustainability, which may be difficult due to the simple construction and design of the products. The review here is based on the case example of the Sulabh pour-flush compost toilet.

Sulabh is a non-profit organisation with a visionary leader in Bindenshwar Pathak [64]. The organisation started to prevent the social issue of manual scavenging and provide dignified labour to a marginalised community [65]. Pathak designed a pour flush toilet where excreta was composted in two deep pits rather than a septic tank [65]. Sulabh NGO then used the toilet design to set up community toilets that people can access at nominal costs. Toilets were also provided to households through grants and government aids. Although the NGO was founded in the 1970s, it is still working to provide access to sanitation in many South Asian countries. The Sulabh toilet has become a quintessential example of appropriate technology and frugal design by having more than 1.2 million toilet units in operation [65]. Table 2.5 presents a summary of strategies employed by this widely successful venture.

Table 2.5: Summary of the design strategies used by Sulabh Pour-flush compost toilet, a notable low-tech group-serving case example.

	Sulabh pour-flush compost toilet
Product Design	Used a <u>simple product architecture</u> and design that enabled easy construction and maintenance [65] <u>Different versions of the product</u> were designed to suit the environmental conditions of varied MCs. [65]
Business and Strategic design	<u>Pay per use models</u> was implemented after surveying community requirements [65]. <u>Pilot models</u> were constructed the community can test before scaling up activities [65].
Service Design	Used <u>monitoring programs</u> that help to sustain and provide upkeep of the products [66] Included additional services and <u>support programs</u> for uplifting population and provided health care provisions [64]
Dissemination and Distribution	<u>Interactive training sessions</u> around sanitation and hygiene were conducted to ensure awareness of the solution [65]. Used <u>novel methods for spreading awareness</u> , such as theatres, street dramas, quizzes, songs apart from household visits [65]. Novel <u>rituals and ceremonies</u> were devised to enable better community transitioning to solution usage [65]. Provided <u>entrepreneurship opportunities</u> for local people to support the solution during usage and maintenance [65].

Although only one case from the group was reviewed, it sufficiently highlighted the focus areas for such solutions. Results indicate that such products need simple, robust and highly maintainable designs. There is also a focus on providing opportunities for income generation to integrate the local population into the value chain. A critical focus of such solutions seems to be in the dissemination and distribution. Since the solutions are designed for community use, devising novel methods of spreading awareness seem to be the key to widespread adoption and thus success. Typically funding agencies neglect this part of the solution, assuming that pilot of the solution will take care of any issues of awareness [65]. Unfortunately, the funding agencies do not consider the significant costs of such awareness activities. Thus, when designing novel solutions that are low-cost and group serving, concepts must integrate novel methods and strategies for creating product awareness apart from devising pilot plans. Furthermore, systems-level concepts must include strategic ways in which community is incorporated to maintain the solution.

2.2.6 Discussion on Analysis of Notable Cases

It can be seen that frugal products exist in each of the four quadrants shown in Table 2.1. However, the nature of the frugal design differs based on the technology and user group they serve. High technology products need significant consideration of product architecture and design features to make them suitable for use in MC's harsh and unreliable conditions. In contrast, low-tech solutions need to develop robust, optimised and simple embodiments that can be easily and locally manufactured. Moreover, products with low-end technologies have a stronger focus on strategic challenges related to service, distribution, and awareness.

Similarly, product and strategic development considerations change when solutions are designed for individual or group use. When designing for group or community use, solutions must be designed to be robust to unintentional and careless usage. Furthermore, they need to consider issues related to vandalism and theft as well. This constraint has a considerable effect on the product embodiment and the service design of the product. On the other hand, designing for individuals must be based on the individual's needs, problems, and aspirations. Furthermore, designers have to consider the end-of-life, affordability and user experience of such products.

The key focus areas for each solution category were extracted based on this review of successful cases. Focus areas are specific aspects of the design process that must be considered in higher detail than others when developing solutions within each category in Table 2.1. For example, when designing low-tech solutions, creating a novel product architecture may be the best way to reduce unit costs. However, the major focus for such products should be optimising the solution to create simple embodiments that are easy to manufacture. The focus areas for different solution types are shown in Table 2.6:

Table 2.6: Focus Areas for different categories of Solutions in marginal contexts.

Focus Areas	Solutions with High-Tech embodiments	Solutions with Low-Tech embodiments
<p>Group Serving Solutions</p>	<p>Product Design Focus is on:</p> <ul style="list-style-type: none"> - Designing solutions that operate robustly in harsh and unreliable environments and usage scenarios - Designing solutions that consume low power - Creating ways to monitor products continuously. <p>Strategic Design Focus is on:</p> <ul style="list-style-type: none"> - Devising suitable PSS and pay-per-use schemes - Collaboration with multiple agencies for finance, service and distribution <p>Service Design Focus is on:</p> <ul style="list-style-type: none"> - Providing services for usage and maintenance of the product - Providing additional products and services to support usage and end of life scenarios. <p>The focus of Dissemination strategies is on:</p> <ul style="list-style-type: none"> - Providing income generation opportunities for the local population by incorporating them into the value chain 	<p>Product Design Focus is on:</p> <ul style="list-style-type: none"> - Optimising solutions to have simple construction, embodiments and manufacturing methods. <p>Strategic Design Focus is on:</p> <ul style="list-style-type: none"> - Devising suitable PSS and pay-per-use schemes - Exploring means financing production and offsetting product costs <p>Service Design Focus is on:</p> <ul style="list-style-type: none"> - Providing means of maintenance, monitoring and upkeep of solutions by involving local people. <p>The focus of Dissemination strategies is on:</p> <ul style="list-style-type: none"> - Designing novel methods for spreading product awareness and educating users about the product benefits. - Providing income generation opportunities for the local population.

Individual Serving Solutions	<p>Product Design Focus is on:</p> <ul style="list-style-type: none"> - Designing multiple solution versions that support various use cases. - Designing novel product architectures for reducing unit costs. - Strict adherence to performance parameters. <p>Strategic Design Focus is on:</p> <ul style="list-style-type: none"> - Devising suitable pay-per-use, microfinancing and PSS models - Employing sustainability measures such as carbon offsetting and carbon credits. - Exploring alternative funding models such as humanitarian aids and grants <p>Service Design Focus is on:</p> <ul style="list-style-type: none"> - Developing services for product use and end of life scenarios <p>The focus of Dissemination strategies is on:</p> <ul style="list-style-type: none"> - Devising unique supportive social programs for creating awareness. - Developing new distributor networks to involve local people and provide income generation opportunities. 	<p>Product Design Focus is on:</p> <ul style="list-style-type: none"> - Optimising solutions to have simple construction, embodiments and manufacturing methods. <p>Strategic Design Focus is on:</p> <ul style="list-style-type: none"> - Exploring financial aids and grants for supporting product development, marketing and scaling up. - Collaborating with multiple organisations and agencies for supporting product development and scaling up. <p>Service Design Focus is on:</p> <ul style="list-style-type: none"> - Developing services for product use and end of life scenarios by training and including local workforce <p>The focus of Dissemination strategies is on:</p> <ul style="list-style-type: none"> - Devising novel and appropriate means of marketing and advertising the product to users. - Creating income generation opportunities for local people - Measuring product impact on people's lives.
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Results of the analysis show some commonalities in the focus areas of the different solution types. When designing high-tech solutions, the product design focus is typically on creating novel product architectures rather than creating low-cost embodiments. There is a strong focus on using PSS and pay-per-use models to improve the affordability of such solutions. On the other hand, product designs of low-tech solutions focus on creating simple solutions that are easy to manufacture locally. The strategic focus for low-tech solutions is identifying suitable financing opportunities to support product development, dissemination and scaling. The focus of dissemination strategies is to create appropriate means of advertising, marketing and spreading awareness of the products

The focus of group-serving solutions is in providing effective means of monitoring and maintaining the solutions when they are in use. The solution also focuses on providing appropriate services and forming meaningful collaborations with various agencies to support the solution. On the other hand, individual serving solutions focus on funding opportunities to support social programs and effective dissemination.

A common focus for all solution types is integrating the local population meaningfully into the value chain and providing income generation opportunities. Also, all types of solutions focus on providing services to support the product during its usage and end of life.

Designers need to deal with the complexities of different kinds when designing the different types of solutions. The review highlighted a need for assessing project complexity and typology of solution before a designer can choose the guidelines, strategies and processes to implement. A

design project's complexity can be assessed using technological fidelity, strategic design requirements and usage pattern. The focus areas uncovered provide some clues for tackling such complexities and delineate the guidelines depending on the typology of the solution.

2.3 Analysing Failed Design Solutions³

Many contributions to frugal design use a case-study approach to develop theories, guidelines, and heuristics. Despite explicit mention, most selected cases in these studies are included in the analysis because they are successful. Unfortunately, this may create an inadvertent bias in the body of knowledge. Furthermore, it may be unavoidable since failed case examples, barring a few, are never reported in academic or non-academic literature.

This section attempts to fill this lacuna partially by collecting and analysing seven cases of failed solutions in MC. A systematic search in academic and non-academic sources was conducted to find examples of unsuccessful solutions for MC. Selected cases from the list were examined to understand why they are reported as failures. Specifically, the design guidelines that the cases followed or did not follow were analysed.

This second part of the case study analysis was conducted to further examine the relative importance of frugal design guidelines. Although the first part highlighted the key focus areas for a design process, specific strategies for its implementation were not elaborated. Therefore, a systematic search and analysis of failed solutions in MC were conducted to fill this lacuna.

Failed case examples in the context of this study are defined as:

“The solutions whose ‘core idea’ have been discontinued from further development by the initiating agency since it did not meet one or more of the primary needs after it was developed. “

‘Core idea’ is defined as the embodied tangible artefact whose primary function leads to fulfilling the primary need or solving a problem.

An underlying hypothesis was that failed solutions do not meet many of the suggested design guidelines for MCs. Although only qualitative analysis is presented with a small sample of cases, the analysis can strengthen the overall value of the design guidelines. Given the results, some changes to the design process when designing solutions for MC are proposed. Additionally, the implication of the study for the frugal mindset is discussed.

2.3.1 Methodology for Analysing Failed Cases

Academic databases were searched for articles where keywords such as ‘failed’ and ‘solutions’ and ‘base of the pyramid’ (and other similar terms) appeared together in the title, abstract, or keywords. Abstracts of around 300 articles were reviewed, and unrelated articles or ones that did

³ Part of the work presented in this section was published in the conference paper: Upadhyay, P., & Punekar, R. M. (2021). What Can Designers Learn from Failed Solutions in BOP Contexts? In *Design for Tomorrow – Volume 3* (pp. 309-324). Springer, Singapore. Some portions of the text from the paper has been reproduced here.

not mention specific cases were eliminated. Failed social innovations and policy interventions were not considered for this search. Seventeen relevant articles were found where specific cases were discussed. Very few articles delved into analysing failed case examples from the design perspective.

Second, a search was conducted in online databases provided by 'engineeringforchange.org'. The database lists products and solutions aimed at one of the sustainable development goals. A list of solutions that the database had marked as 'discontinued' was selected. Many such discontinued products were replaced by a better version or were still distributed under a different name. Such solutions did not fit our criteria of a 'Failed Case'.



Figure 2.12: Images of Failed Case examples selected for Analysis. Clockwise from top left: Tata Nano, Uncharted Play's Soccer, Playpumps Roundabout, Aakash tablet, Simputer, OLPC's XO laptop and Polaris Multitax.

Solutions with unreliable literature (e.g. non-peer-reviewed sources, blogs and unreputed media outlets) were removed from the review. A web search using a combination of relevant keywords was then conducted to further enrich the list of failed cases. Finally, the author's peer networks were approached to suggest some examples of failed case examples. Many of the cases suggested by peers had already been collected, which indicated that saturation was occurring. From all the searches, a total of seven cases could fit our criteria and were analysed further. Figure 2.12 shows the cases selected for the study.

The literature was reviewed to formulate a framework for evaluating the selected cases. Several authors have written about the design process for the context [1], [67]. A common notion is that there is a significant difference between the typical design, development, business, and dissemination processes and the corresponding processes for MCs [68]–[70]. Additionally, several authors have tried to inform the design process by collecting and proposing guidelines from relevant literature [7], [71]. The most recent and comprehensive review to inform the design process for emerging contexts was given by Jagtap [7].

Jagtap proposes ten guidelines to inform the design practice for marginal contexts [7]. Due to this literature's recency and breadth, these ten guidelines were used to formulate a framework for the analysis. Specifically, 14 questions were formulated based on the guidelines to thoroughly review each selected case example. These questions are presented in the table below:

Table 2.7: Framework for analysing Failed Case examples of Frugal Design.

Title	Question
Q1 Holistic understanding	Is there evidence of holistic knowledge of marginalised communities and the context?
Q2 User's daily life	Is there evidence of a deep understanding of the user's daily life?
Q3 Co-Design	Is there evidence that a co-design process was used at key stages of the design process? (key stages are: understanding needs, concept generation, concept selection)
Q4 Adaptation	Is there evidence that the solution (or its parts) was contextualised or adapted to suit the scenarios in which it was deployed?
Q5 Leverage social strength	Is there evidence that the solution leveraged local socio-cultural strengths of the communities where and when it was deployed?
Q6 Used existing infrastructure	Is there evidence that the solution used the strength of existing infrastructure, products, or resources in the context?
Q7 Training Programs	Is there evidence that the solution provided training programs to the actors to implement, use, or maintain the solution?
Q8 Income opportunities	Is there evidence that the solution provided income generation opportunities for increased income from current means directly or indirectly?
Q9 Appropriate Awareness	Is there evidence that the solution employed means of creating awareness that was contextually appropriate and suitable to the literacy level in the context?
Q10 Services	Is there evidence that contextually appropriate services or support were provided for post-use and end of life scenarios?
Q11 Reliability	Is there evidence that the solution is designed to be robust, reliable and resilient to the extreme environment or usage pattern?
Q12 End of Life	Is the solution designed to be easy to repair, upgrade, adapt or modify?
Q13 Collaboration	Is there evidence of collaboration and partnerships in various stages of the solution's lifecycle?
Q14 Desirability	Is there evidence that the solution considered aesthetics, usability, ergonomics and other such desirability factors?

2.3.2 Results of Analysing Failed Cases

Following the methodology for analysis, relevant literature was identified in academic and non-academic sources to evaluate each failed case example. The following set of tables provides a condensed view of each analysis.

2.3.2.1 Case 1 – The Tata Nano



Figure 2.13: Tata Nano, Image source: Wikimedia commons

The Tata Nano was termed the ‘world cheapest car’ designed and developed in India by Tata Automobiles. It is a high-tech individual serving product. It is one of the most unique case examples due to the polarising discussions available in the literature. Where several authors who have analysed its design and development consider it a quintessential example of frugal innovation [17], [72], [73], the product failed to meet customer expectations, and reports suggest that production may halt in 2020 [74]. Due to this, Tata Nano remains a controversial example of Frugal design and hence is pertinent to academically assess its development life cycle.

The Core Idea of Tata Nano was to create an affordable car for people whose primary family transport is a two-wheeler [17]. After its much-fanfare release, several reports suggested that it was not accepted well in the market. Reports indicate that the product failed due to poor on-road performance, production problems due to political issues, lack of manufacturing capacity at initial stages, Marketing and product positioning problems [18], [75]. The following list provides a snapshot view of the case analysis based on the framework in Table 3 and using existing literature and reports [17], [18], [76]:

- **Q1 Holistic understanding:** Somewhat. The development team communicated continuously with communities during the development of other products and used the experience;
- **Q3 Co-Design:** Somewhat. The team collaborated with suppliers and manufacturers early in the development process to find new and novel ideas for cost reduction. No information was found regarding co-design with users.
- **Q4 Adaptation:** Yes. Modification of Supply chain, Special financing schemes in collaboration with banks
- **Q6 Used existing infrastructure:** Yes. The suppliers, workforce and infrastructure used for the development of exiting products were leveraged
- **Q7 Training Programs:** Yes. Franchisees were given training on assembly and servicing.
- **Q8 Income opportunities:** Somewhat. The company encouraged local franchisees.
- **Q9 Appropriate Awareness:** No. The marketing and positioning of the product were not well received by consumers.
- **Q10 Services:** Somewhat. Post-purchase services were available.
- **Q11 Reliability:** No. Although the product met some international guidelines, it was unreliable in the field.
- **Q12 End of Life:** Somewhat. Due to the reduced complexity in assembly than other models.
- **Q13 Collaboration:** Yes. With suppliers
- **Q14 Desirability:** Yes. An external design agency was used to design the vehicle.
- Other Questions could not be assessed due to inadequate information.

2.3.2.2 Case 2 - Soccer by Uncharted Play



Figure 2.14: Uncharted Play Soccer ball. Image source: Engineering4Change

Soccket by Uncharted Play is a football that could harness and store energy when kicked around. It is a high-technology individual-serving solution. The energy can be used to light up an LED or charge up devices later on. The core need was to provide power in inaccessible and off-grid scenarios in marginal contexts. The indicated reasons for product failure were: an unclear understanding of the usage patterns [77], [78], Performance Issues and reliability issues [78], [79]. Since then, the company has been renamed 'Uncharted power' and primarily focuses on other stray energy harnessing solutions. Based on the existing media reports [77], [78], the case was assessed as follows:

- **Q1 Holistic understanding:** Somewhat. The product was aimed at communities where soccer is the main form of play. However, it was unclear if other aspects and impact on the context was assessed
- **Q2 User's daily life:** No. The play-to-light ratio and the fact that several children would use one ball during play, but all these children would need light at the end of the day, indicates this.
- **Q3 Co-Design:** Somewhat. User test with prototypes and extensive giveaway models was used to improve the design. However, evidence was not found that co-design activities were used in all phases.
- **Q4 Adaptation:** Somewhat. In terms of product design and business model. E.g. a donation scheme of buy-one-give-one and play to donate were used.
- **Q11 Reliability:** No. The product was unreliable for several users and broke down after some play in the actual context. However, reports indicated that only around 3 % of the products failed.
- **Q14 Desirability:** Yes. The initial reports of reception and user feedback were positive.
- Other Questions could not be assessed due to inadequate information.

2.3.2.3 Case 3 - Roundabout Playpumps



Figure 2.15: Children playing on the Playpumps Roundabout. Image Source: Playpumps.org

Roundabout Playpumps were playground equipment that could mechanically power a water pump. It was a low-tech group-serving solution. The community could then use the stored water. The product also had an advertisement board attached to it, the revenue from which was planned to be channelled towards product maintenance. The product has been comprehensively analysed in the PhD thesis by Borland [80]. The main reasons for failure were an unclear understanding of the user's lives, product performance, unenvisioned usage patterns and flawed calculation of water usage patterns. Based on Borland's research and some supporting material [81], the case was analysed as follows:

- Q1 Holistic understanding: Somewhat. The promoter hit upon the idea when installing other water pumping solutions in the context. However, there is no evidence that a holistic understanding was pursued after the idea kick-off.
- Q2 User's daily life: No. It is reflected in the large amount of playtime required for pumping and the reluctance of advertisers to advertise in such settings.
- Q3 Co-Design: Unclear, but overall reports point to a negative.
- Q4 Adaptation: Yes. The product was locally manufactured.
- Q6 Used existing infrastructure: Yes. The product was locally manufactured
- Q8 Income opportunities: Somewhat. Indirectly by providing clean water.
- Q9 Appropriate Awareness: Yes. Community-level programs and installations
- Q10 Services: No. Many Playpumps failed and could not be maintained due to the initial plan of advertisement not generating enough money.
- Q11 Reliability: No. Many Playpumps failed in the harsh conditions of the field.
- Q12 End of Life: No. Playpumps were abandoned and were not used as intended
- Q14 Desirability: No. The system was mostly designed to appeal to the funding and supporting agencies than the user.
- Other Questions could not be assessed due to inadequate information.

2.3.2.4 Case 4 – OLPC XO laptop



Figure 2.16: XO laptop by One Laptop Per Child. Image Source: Wikimedia commons

One Laptop Per Child's XO laptop was a low-cost laptop designed for underprivileged children in remote locations of the emerging contexts. The product was a high-tech individual serving solution. The basic need was to provide the children with a means of self-learning [82]. The indicated reasons for failure were an unclear understanding of the context and educational infrastructure in the developing world, production and sourcing issues, performance, infrastructure issues and competitor products [83], [84]. The case was analysed based on some existing reports [84]–[87] and literature [82], [88], [89] as follows:

- Q1 Holistic understanding: No. An unclear understanding of the context and the infrastructure is one of the reasons cited as a failure.
- Q2 User's daily life: No. The promoters did not consider how the student will use the product in their daily lives and an educational context.
- Q3 Co-Design: Somewhat. Several product prototypes were given to users for feedback and design ideas.
- Q4 Adaptation: Yes. The design incorporated a hand-crank mechanism to generate power, novel hardware, operating system and interface.
- Q6 Used existing infrastructure: No. The local infrastructure such as electricity availability, curriculum and educational infrastructure was not considered.
- Q7 Training Programs: Somewhat. The deployment agencies provided some teacher training in specific countries.

- Q8 Income opportunities: No. the company primarily sold the products to developing nations.
- Q10 Services: No. Lack of services provided in one point of critique of the product.
- Q11 Reliability: Somewhat. Although the product was built tough, the internal hardware and software failed in many cases.
- Q14 Desirability: Yes. The product and the UI were designed by a Start designer Yves Béhar.
- Other Questions could not be assessed due to inadequate information.

2.3.2.5 Case 5 - Multix by Polaris



Figure 2.17: Multix by Polaris. Image Source: Motoroids.com

Multix by Polaris was a multi-use carrier and passenger vehicle where the engine power could provide electricity or power various equipment such as water pumps through a connector mechanism. The product is a high-tech individual serving solution. The core need was to provide a multi-purpose means of transportation in rural Indian contexts [90]. The product was a joint venture between Eicher Motors in India and Polaris in the US. The joint venture has since been dissolved, and the production was discontinued in 2018. The Main reported reasons for failure were inadequate sales. The product was assessed based on a few reports which exist [91], [92]:

- Q4 Adaptation: Yes. The product trunk could be expanded, and the functionality of the connector mechanism suggests this.
- Q8 Income opportunities: Yes. The product enables the connection of items such as flour mills and water pumps.
- Q10 Services: Somewhat. General sales services were provided.
- Other Questions could not be assessed due to inadequate information available.

2.3.2.6 Case 6: Simputer



Figure 2.18: Simputer handheld PDA. Image source: cse.iitb.ac.in

Simputer was a small handheld computer designed for educational purposes in the Indian context. The core need was to provide data access and computing for communities in the rural Indian contexts [93]. Due to this, the solution can be categorised as a high-tech group serving solution as well. The product's indicated failure was lack of manufacturing facilities in context, perceived risk, lack of training and marketing [94], [95]. Our analysis based on some key resources [93], [96]–[98] are as follows:

- Q1 Holistic understanding: Somewhat. The designers considered that a village could have one device used by multiple people.
- Q4 Adaptation: Yes. The device used smart cards and AAA batteries in case of an unreliable power source.

- Q6 Used existing infrastructure: No. This aspect is one of the reasons cited for failure. There was a lack of manufacturing facilities in India at the time.
- Q8 Income opportunities: Somewhat. The nature of the plan would have created job opportunities in the context, e.g., a device operator at the village level.
- Q9 Appropriate Awareness: No. marketing is cited as a reason for failure.
- Q10 Services: Somewhat. Basic service was provided.
- Q11 Reliability: Yes. The device was well built and suitable for use in the context.
- Q14 Desirability: Somewhat. The device was well-engineered, but the other desirability aspects could not be assessed.
- Other Questions could not be assessed due to inadequate information.

2.3.2.7 Case 7- Aakash tablet



Figure 2.19: Former Indian minister of education Mr Kapil Sibbal unveiling the Aakash tablet. Image source: Forbes India

Aakash tablet (a.k.a Ubislate 7+) was an android tablet aimed for educational purposes in Indian contexts. The product was a high-tech individual serving solution. The basic need was to provide a digital device to students in India [95]. The indicated reasons for failure were manufacturing issues, unfavourable media reports, performance and political reasons. Based on some key reports and literature[95], the product was analysed as follows:

- Q1 Holistic understanding: No. The idea of the device was borrowed from other cheaper tablets and computers.
- Q6 Used existing infrastructure: No. The promoters focused on outsourcing the device to agencies outside of the context.
- Q9 Appropriate Awareness: No. Reports do not suggest any unique or appropriate forms of awareness campaign outside of launches and unveilings.
- Q11 Reliability: No. The device was unreliable and underpowered in use.
- Q13 Collaboration: Somewhat. Several agencies collaborated in developing and manufacturing the device, but this was forced rather than amicable.
- Other Questions could not be assessed due to inadequate information.

Our search found many other examples deemed failed by multiple sources but could not be included in the list due to our inclusion criteria and definition of failure. For instance, Vestergaard's LifeStraw®, a water filtering product, is considered a failure by some [99], [100] due to its prohibitively high cost. Still, the technology has been diversified into several products since its introduction. The idea is not abandoned, and thus the product cannot be considered a failure as per our definition. Similarly, several examples of discontinued products in the *engineering4change* database were found. However, the underlying technology was taken further to develop other products for the same contexts or upgraded. From a total of 29 case examples of discontinued products from the 'engineering for change' database, only one case fit our criteria, that of the Uncharted Play Soccket. The remaining 28 examples were either replaced by a better version of the product, were open-source designs, distributed under a different brand name, or did not have enough information to evaluate them.

2.3.3 Discussion on Analysis of Failed Cases

The first thing to note is that few case examples have been reported and analysed. Although the intention was to find a significant number of failed cases examples, our systematic search could not identify many. This fact strengthens the assumption that failed case examples are not discussed adequately in literature or media unless they are high profile.

In our analysis, Tata Nano was a unique and fascinating case example. The product was deemed a success at launch and praised as a quintessential example of frugal engineering and frugal design [101]. Many academic papers use the example of the success of Tata Nano to frame suggestions and guidelines [17], [73]. Tata Nano was a success during its lifecycle, from idea conception to commercialisation. However, it failed after it was released into the open competitive market. This fact indicates that 'product failure' can happen at different stages of the development lifecycle. Adapting the suggestion of Dana et al. [102] for dividing the lifecycle of a grassroots innovation project, three stages of failure can be defined: Failure at the inception phase, failure at the protective niche phase, failure in the open market. Designers and researchers can analyse their products at these distinct lifecycle stages and report the shortcomings for analysis and theory building.

Our analysis shows that most of the failed cases did not meet the design guidelines presented. Thus, these guidelines are invaluable for the designer to assess their projects. Additionally, failed case examples had a lesser understanding of the overall context and users' daily lives. As suggested by many prior articles [1], [7], [103], a deep understanding of the context and users' daily lives is essential for successful design in marginal contexts. Designers should approach the process with a researcher's mindset (and a hypothesis) that their initial idea does not solve the envisioned design problem in the context. Through understanding the context and users' daily lives, the designer can then disapprove of this notion (or land upon the right idea) and design a better product.

It was found that most solutions did not perform adequately in the context. A co-design approach and constant testing of the idea in the context could be used as a remedial measure. Additionally, strategies such as design for manufacturing (DFM), Design Failure-Modes and Effects Analysis (DFMEA), and reliability engineering tools should be used when developing the product. Correct performance parameters should be prepared with a co-designed approach, and the product should meet this target. Repeated testing of the product prototypes should be done in context to alleviate such problems.

Finally, our analysis of the cases has strengthened the case of developing tools based on the guidelines. The instructions are relatively generalised, and novice designers may not clearly understand how to implement them in their projects. Implementing these guidelines into tools that can be applied in specific design stages is undoubtedly needed.

The failed cases identified were from all the quadrants of Table 2.1, which means that only the high-technology products are not prone to failure. Based on the analysis of the failed case examples, the essential guidelines for designers to implement in MC can be highlighted. Thus, some specific ways to implement these guidelines in a Frugal Design project can be provided. Table 2.8 summarises these essential guidelines and concrete ways for implementing them.

Table 2.8: Key guidelines for Frugal Design in marginal contexts and specific ways to implement them.

	Key Design Guidelines that are essential to implement for Frugal Design in MC.	Concrete ways to implement the guidelines
Product Design Guidelines	Designers ⁴ must gain a deep and holistic understanding of the context, including its people, institutional support and infrastructure	Using design research and ethnographic methods such as visual ethnography, interviews, on-field observational studies and understanding contextual constraints
	Designers must gain a deep understanding of the primary user's daily lives, the use cases for the product and how the product integrates into the daily lives of the users	Using design research and ethnographic methods such as interviews, shadowing and contextual inquiry.
	All prominent design stages must be implemented using a co-design approach in collaboration with users and important stakeholders.	Using appropriately modified co-design tools that are suitable for MC. Strategies such as gamified co-design [104] and card sorting [105] can also be used.
	The product must adequately fulfil the intended need and be extremely reliable in performance, considering unforeseen usage, unreliable infrastructure, and harsh environments.	Using tools for engineering design and reliability such as DFMEA, DFM, Fault Tree Analysis, FEA, and constant testing of product prototypes considering different use cases.
Business and Strategic Design Guidelines	Designers must assess existing infrastructure and institutional support and create solutions that leverage it or can work within the constraints	Design research and ethnographic methods can be used to assess the context. Co-design activities with community members can be used to develop appropriate ideas for leveraging existing infrastructure.
	Designers must integrate income-generating opportunities with the solution.	Using systems design approaches such as PSS, appropriate business models and collaboration with financing agencies.
	Designers must integrate various community and skill development activities with their overall solution, such as social programs, technical training.	Co-design activities with prominent community members can devise appropriate social and technical programs to support the product and the community. Collaboration with appropriate social agencies can help to execute the programs.
Service Design Guidelines	Designers must conceive of appropriate services to provide with the product. At the very least, services for product maintenance, use and end of life must be provided	Various service design methods and approaches can be used to develop appropriate services to support the product. Collaboration with supporting agencies can help to implement the services.
Dissemination and Distribution Guidelines	Designers must create appropriate and novel means of creating awareness considering the solution.	Using creative ideation methods and co-design activities with users and prominent community members.

⁴ The terms 'designers', 'design practitioners' and 'design teams' denote interdisciplinary teams who collaboratively conceptualise solutions for user needs and have been used interchangeably in this thesis.

	Designers must assess the solution's performance at three specific phases: inception, protective niche, and open market.	Using subjective and objective concept evaluation and impact assessment methods implemented at multiple design stages, i.e. when a concept is finalised, when a concept is piloted and when the solution is put on the market.
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There are some limitations to the study of failed case examples. First and foremost, this cannot be considered a comprehensive analysis of each case's design process. Additionally, the findings do not indicate causality, nor they can answer questions like 'why do products fail in the market?'. Although beneficial for designers, such a comprehensive review was out of the scope of this chapter.

Finally, it is important to acknowledge that the word 'Failed Product' may have some political and negative connotations, which was avoided in this article as far as possible. Nonetheless, some may still argue that several aspects of these cases were successful, which is indeed true. Our intention is not to ostracise these innovative products or the people behind them but only learn from each case example. Our only goal was to strengthen the current understanding of design guidelines for product development in marginal contexts.

2.4 Discussion

The case analysis provided a list of focus areas for the design process considering different solution types. As evident, all design guidelines and recommendations are not equally applicable to all product types. It was found that high technology products needed consideration of product architecture, whereas low-tech solutions needed a higher focus on devising optimised embodiments for reliable usage and local manufacturing.

Similarly, strategic considerations also change when designing solutions for individual or group use. For group use, solutions robust design is the primary focus, whereas individual use solutions depend on adequately fulfilling needs, problems, and aspirations. This insight confirms that a 'degree of applicability' exists for design guidelines and processes depending on the solution's complexity. Although it is important to align with most design guidelines and processes as far as possible, some should take precedence based on the design project or MC being served.

On the other hand, project complexity does not just depend on the embodiment of the product. For example, for Sulabh toilets, Wellow wheels and IDE Treadle pumps, many strategic design decisions have to be made even in products with low-complexity embodiments. The project complexity thus can be described as the ambiguity faced in making design decisions related to product embodiment and strategies combined. Results indicate that project complexity is specifically dependent on the following:

- 1 The solution requires atypical business models, value chains and payment methods.
- 2 The solution requires supporting services for consumables, upkeep and disposal of the (parts of the) solution.
- 3 The solution requires unique and atypical means of distributing, advertising and disseminating solutions.

- 4 The project focuses on implementing sustainable practices and the use of carbon offsetting methods
- 5 There is ambiguity in the functionality, embodiment and construction of the product
- 6 The solution's impact on the context and users' lives can only be measured long-term.

A key insight from the analysis of failed solutions was that failure of a solution could happen when the solution is at distinct phases of inception, protective niche or open market. The analysis also resulted in a list of the critical design guidelines for all solutions. Some concrete ways to implement the said guidelines were also derived. The study highlighted that contextual design research, co-design, collaboration, systems approaches and using existing design tools are good ways to implement the guidelines.

2.5 Conclusion

The analysis of case examples discussed in this chapter provides the building block for a frugal design approach.

Two related case analysis studies were reported in this chapter. In the first one, notable cases of frugal design were analysed to understand how the design process may change depending on the type of products being designed. A select set of cases were analysed based on the available literature, which resulted in a set of 'focus areas' for the design process depending on the solution type. The role of complexity and its effect on the design process was understood.

In the second part of the study, case examples of failed solutions were systematically searched and analysed. A working definition of a failed solution was presented, and the cases were assessed based on the guidelines for designing frugal solutions in MC found in the literature. The analysis resulted in a deeper understanding of how frugal products could fail. Specifically, a list of the most important design guidelines and ways to implement them were deciphered.

The research illustrated the importance of deep contextual research and participatory approaches in successfully implementing a frugal design approach. A set of criteria to assess the complexity of a frugal design project was presented, among other outcomes.

There are some notable limitations to the studies presented here. Firstly, the attempt in each case analysis was to go in-depth, due to which relatively smaller sample sizes were used. However, case study analyses with similarly small sample sizes have been reported in related literature [106]–[108]. It should also be noted that the selected cases were not from a specific geographical location (e.g. Asia); hence any geography-specific insights might not have been uncovered. However, since the cases belonged to multiple countries, the insights are relatively generalised.

Still, due to the qualitative nature of case study analysis methods, outcomes depend on the interpretation by the researcher to some degree. This limitation makes the results difficult to generalise beyond the context of this research. The results from the study are directed toward creating a structured approach for frugal design, thus must be interpreted accordingly.

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Chapter 3 Retrospective Analysis of Design Projects

Design researchers need to don the practitioner's hat to appreciate the applicability of theories and supports they develop. Therefore, the author was engaged in several parallelly executed design projects during this research. The aim was to understand and experience the challenges and constraints of frugal design for marginal contexts (MC) from a practitioner's perspective. This chapter presents a retrospective analysis of four of these projects where the author worked as a designer and supervisor. The study identifies certain constraints presented by the MC, challenges faced in implementing the design recommendations, and the requirements for a systematic approach to frugal design.

The projects were selected for review since each one followed a unique process and incorporated design recommendations found in the literature to varying degrees. The contrast between each project highlights the intricacies of frugal design in MC. The study was termed a retrospective analysis since it critically reviews each project's process to derive relevant insights.

3.1 What is a Retrospective Analysis

There are definite constraints that can impede a designers intention to follow any specific design guidelines for MC [1], [2]. Such constraints depend on the type of products [2] and the nature of MCs [3]. Unfortunately, the constraints faced when designing frugal solutions are not evident simply by looking at the outcomes or, in other words, analysing existing cases in the market.

A shortcoming of analysing existing case examples is that limited information is available on specific design decisions and activities for thorough analysis. This lacuna makes it difficult to fully understand their design process and its challenges. As part of academic and professional engagements, several design projects related to MC could be completed during the timeline of this research. The experience from these projects helped in critically analysing the outcomes and process followed in light of the existing frugal design recommendations, strategies and guidelines. This chapter presents a retrospective analysis of the immersive experience in four design projects related to MC.

Retrospective analysis is a methodology where knowledge, experience, and documentation from prior work is used for understanding or evaluating any newly developed theoretical constructs. Retrospective analyses have been used to devise new design guidelines [4], validate new theoretical frameworks [5] and also understand the effectiveness of newly designed tools [6]. This research uses a retrospective analysis to uncover the challenges and constraints faced by design practitioners when executing projects for MC.

One of the ways in-depth records of the design process and experience of designers can be uncovered is by interviewing practitioners. Still, some aspects of their experience may not be uncovered if structured interviewing protocols are followed. With unstructured interviews, data

generated may be large, thus making it difficult to analyse. Also, design documentation, internal communication, and prototypes may reveal many facets of the process that are inaccessible when following an interview methodology. Therefore, a retrospective analysis where the researcher played a designer's role in developing the solutions was seen as promising. This process ensured that the tacit knowledge and experience were easily accessible for critical review, apart from the extensive design documentation and the detailed outcomes.

The four design projects chosen for the retrospective analysis were completed between 2016 and 2020. The projects were chosen to represent varying levels of complexity, development time and incorporation of state-of-art design guidelines. The analysis results outline a set of general requirements for a systematic frugal design approach for MCs. These requirements were based on the experiences and needs identified during the design projects. In the following sections, each project is elaborated, and a summary of analysis outcomes is presented.

The discussion section describes the general requirements for a frugal design approach and the constraints in executing design projects in MC. The chapter concludes with a reflection on the work done and some key insights related to a frugal design approach.

3.2 Project 1: Design of a vegetable vending station

Small fruit and vegetable vendors are common sights in India. Most of these sellers belong to the marginalised sections of society. Since they do not have permanent shops, they are forced to transport their produce every day from faraway locations. They do not have access to storage and refrigeration facilities, resulting in much waste, and their businesses are highly unorganised.

3.2.1 Project Brief and Design process

This project was initiated in collaboration with The Guwahati Municipal Corporation (GMC), who wanted to transform certain city locations into modern and hygienic marketplaces. GMC had the vision to construct unique stations for fruit and vegetable vendors who did not own a permanent shop. Most vendors were from the poorer sections of society with low daily incomes. These vending stations could be rented at nominal costs to the vendors and maintained by the administration. With such stations, GMC could also control the allocation of selling space to vendors, thus ensuring fair competition.

The target users were seasonal sellers of vegetables, which meant that the scenario was ad-hoc and dependent on the availability of nearby resources. In order to improve the scenario, GMC constructed paved platforms and pathways with garbage and water management facilities. Infrastructure for sanitation, drinking water and overall beautification was planned and implemented. It was envisioned that the vending stations would add to this plan by creating a model 'bazaar' with a unique visual identity for Guwahati city.

Based on this design problem was set as: "Design a method for selling fruits and vegetables which will be used by seasonal sellers who do not currently have established shops."

The design process was completed in two months, from inception to prototype development and delivery. A two-member team designed the solution in collaboration with representatives from GMC, and an MSME handled the prototype development. A classical approach to design was used for this project with the following broad stages: 1) Gathering requirements and design brief, 2) User research through observational studies, 3) Need analysis, development of product requirements and specifications, 4) Concept generation, and 5) Prototype development and testing. Comprehensive pilot testing and deployment were not part of the design project as per the design brief and client directions.

Formative requirements, initial technical specifications and a design brief were provided by the client and reviewed by the design team. User research was primarily conducted through field visits, contextual observations, and in-situ interviews with vendors. The design research results were analysed using typical methodologies [7, p. 75], and the concept generation was done using brainstorming approaches. The prototype was developed in collaboration with a local MSME. The product testing and pilot evaluation of the solution were not part of the design brief.

Finally, the product was a vegetable and fruits vending station made using a tubular frame, collapsible canopy, and multiple platforms to display the produce. The canopy used graphics adapted from traditional textile and contained space for standardised branding.

Section N.1 in **Appendix N** Shows several images of various stages in the development process. Figures 3.1 and 3.2 show the context and the final designed solution.



Figure 3.1: Various vegetable vendors at the location.



Figure 3.2: Final prototype on location.

3.2.2 Retrospective analysis of the project

Although the design and development were completed within the stipulated duration, it was not a major success. In hindsight, following a typical approach inhibited the designers from conceiving a holistic solution. Due to this, many of the guidelines for frugal design were not adequately met during the development. The experience in designing this product highlighted the importance of deep user research. The solution did not fully meet all vendors' expectations due to the lack of understanding of their daily lives. For example, many vendors used jute bags, cloths and bamboo weaved baskets to transport the produce. The solution did not have enough space to store these items when they were not used. Also, the vending station had platforms where plastic containers

could be used to display the produce. Later testing found that only a handful of vendors had access to these plastic containers.

In retrospect, such issues seem obvious requirements for the solution. However, due to a lack of deep understanding of the constraints, such requirements could not be uncovered at early design phases. Moreover, given the limited timeframe of the project and the lack of a clear framework for identifying the constraints, designers faced the challenge of uncovering the right requirements.

The project was retrospectively analysed based on the key design guidelines identified in Table 2.8 (Chapter 2). For each guideline, the specific design activities conducted and the limitations of those activities were recorded. Table 3.1 shows a summary of the analysis:

Table 3.1: Summary of retrospective analysis of the project: Design of fruit and vegetable vending station.

Key design guidelines	Activities Conducted in the project	Limitations of the project activities
Designers must gain a deep and a holistic understanding of the context	Observational studies were conducted in multiple field visits.	An in-depth field visit could not be conducted due to less time. Holistic understanding of context was lacking due to the unavailability of appropriate frameworks for assessing the context.
Designers must gain a deep understanding of the primary user's daily lives	Basic observational studies and interviews with vendors were conducted	Following typical NPD process did not allow for in-depth assessment of the daily lives of users In retrospect, the designers were unsure if such in-depth study was required for the project.
Design stages must be implemented using a co-design approach	Co-design activities were not done with vendors and prominent stakeholders.	Designers felt that typical NPD approaches were adequate.
Products must fulfil the need and be reliable in performance	Basic CAD analyses were used to design the product.	Specific reliability engineering methods were not implemented due to the short scope of the project.
Designers must assess existing infrastructure	Existing infrastructure in the context was analysed through field visits	The design team did not analyse the context's political practices and legal enforcement.
Designers must integrate income-generating opportunities	Specific business models were not developed. However, the product was developed to support existing income generation activities.	Development of value chains was not considered since the team followed a typical NPD process.
Designers must integrate various community and skill development activities	Co-design activities were not done. The design team only collaborated with the manufacturer for prototyping.	The process followed did not allow for such activities.

Designers must conceive of appropriate services to provide with the product	Basic maintenance and upkeep services were discussed with the clients.	The project scope was limited; thus, the design output did not consider such activities.
Designers must create appropriate and novel means of creating awareness	Not considered in the project.	Activities related to this were not considered with the project scope.
Designers must assess the solution's performance	Evaluation of the concept was done using interviews.	Product was only assessed in technical parameters. Evaluation in social parameters was not done due to inadequate understanding.

3.2.2.1 Project Challenges and Constraints

One of the major challenges faced in the project was understanding how geographical factors and social practices affected the solution. Critical design requirements were missed since the design team did not consider any specific frameworks for understanding or informing the research process. For example, when the team evaluated the product, one vendor stated they needed to pay some local agents to use the space for a certain duration. In return, these agents provided the vendors with LED lamps and tarpaulins to set up their shop. Although these agents are not strictly part of a structured system, their presence ensures that space is shared between the vendors effectively. The solution essentially bypassed these agents, which, the vendors felt, would create a rift in the social structure of the 'bazaar'.

Furthermore, since the vendors were not permanent in the location, their daily lives were strongly dictated by their ability to transport their products safely. For them, an ideal solution needed means to store some valuables. However, this requirement conflicted with the client brief who wanted to provide access to solutions on a daily fee basis. It could not be ensured that vendors get the same station every day with such a plan. Moreover, they needed multiple bags, crates, and baskets to transport their goods. In a shop, they used such items to display the produce. The new design made it difficult to accommodate their existing practices into the workflow, thus inhibiting them from using the solution effectively.

The analysis of this case emphasised the importance of understanding social practices and political relationships in the context. Furthermore, the designers need to be informed of the various guidelines for designing in MC, and it should be done through appropriate frameworks. It is unwise to assume that only a deep immersion in the contexts or stringently following NPD processes would be enough to arrive at appropriate solutions. Specific design processes and approaches are needed to implement the design guidelines effectively. It is also important to allocate time and resources to design activities for such deep user research. Furthermore, even when engaging with a structured design brief, it is important to broaden the project scope appropriately after discussing with clients.

3.3 Project 2: Design of PoCT Device for PHCs

Public Healthcare Centres (PHCs) are small scale setups that provide healthcare access to the rural and urban populations across India at minimal costs. These state-funded institutions provide preventive and curative health services and are the backbone of the country's healthcare setup. Although PHCs enable accessible healthcare to a large population, the quality of services is not comparable to private hospitals due to a lack of infrastructure, equipment and skilled labour [8]. More than thirty thousand PHCs exist in India [9], indicating the scale of this MC.

Point of Care Testing (PoCT) Devices are a class of medical equipment that provides an alternative to centralised laboratory testing and are typically price accessible, portable, and user-friendly. An example of a PoCT device is a handheld blood sugar monitoring device. Tabletop scale PoCT devices also exist, which provide a means of conducting specific diagnostic tests without dependencies on other laboratory infrastructure (e.g. portable ECG machines, spirometers and Ultrasound machines) [10]. PoCT devices provide an obvious advantage for healthcare and diagnostic in PHCs [10]. Since most devices are self-contained, portable and low-cost, they are easily accessible to PHCs. Moreover, typically PoCT devices have a relatively low skill standard operating procedure, making them easy to use by semi-skilled staff. In addition, the scale of the PHC in India makes the design of specific PoCT devices for the scenario a pertinent design direction.

3.3.1 Project Brief and Design process

In this collaborative project, an interdisciplinary design team from the Department of Design and Centre for Nanotechnology, IIT Guwahati, aimed to design PoCT devices for semi-urban and rural MCs in India. State of the art technology using paper-based biomarker sensors was developed by the Centre for Nanotechnology IIT Guwahati [11]–[13], which the design team used for creating modular PoCT diagnostic devices. The project was part of the final year bachelors' thesis in which the author played a supervisory role. The project aimed to design and develop affordable and modular PoCT devices for diagnosing specific ailments in rural and semi-urban PHCs using paper-based biomarker sensors.

The focus of this project was on gaining an in-depth understanding of the MC, following prior design experiences and acknowledging the academic setting for product development. The following process was followed for the project:

- 1 **Benchmark Study and technology analysis:** The project started with the search for existing PoCT devices and their analysis. This review provided the landscape of existing solutions and their design considerations. Existing technologies developed by collaborators were analysed to understand how these could be transformed into marketable products. Literature was reviewed to identify key impact areas and design opportunities. The designers found scope for many low-cost interventions, such as blood sugar monitoring, albumin-creatinine ratios, testing lung functions. However, not all were relevant, considering the potential impact and the MC. The team decided to develop a modular PoCT device for PHCs that could accomplish common tests which required more skill, time, or resources.

- 2 **Observational Studies and Problem Clarification:** In this stage, the design team conducted field visits to several PHCs and conducted observational studies and interviews with people in situ. The goal was to understand the specific constraints in the MC and identify opportunity areas that the selected technologies could fulfil. This design research generated insights, opportunity areas and clarified problems faced by the users. Specific design requirements for different types of PoCT devices were also gathered. The team then tested their assumptions for the need, assessed how PoCT devices were used in the context and identified constraints that affected the design.
- 3 **Ideation and Concept Generation:** Following the finalisation of the project brief, the design team collaboratively generated ideas for various types of PoCT devices needed in the PHCs. The concepts were generated in multiple sessions following traditional brainstorming methods and short co-design sessions with technicians in the PHCs. One design concept was finalised for further development. The concept enabled multiple diagnostic tests using paper strips that indicated the presence of certain biomarkers. The strips were 'read' using measurement methods of photometry and electrical conductivity. The concept contained modules that could be swapped to modify the test type and measurement methods. The device was then made modular and easily upgradable by designing swappable internal components.
- 4 **Iterative concept development:** The selected concept was iteratively developed through a cycle of mockup-prototyping-testing-finalisation. Several additional products were also conceived to help the design concepts operation in the field when designing the product concept. E.g. a case for effectively storing and disposing of paper test strips was developed. The modular product architecture increased the upgradability, maintenance and affordability of the PoCT device. CAD software was used for assessing various aspects of the device and for prototyping.
- 5 **User testing and clinical trials:** designers developed appropriate user interfaces (UI) to make the PoCT device operation easy for semi-skilled technicians in the PHCs. Simultaneously, a functional model of the product was developed following the concept vision as closely as possible. The UI was tested with the PHC technicians and modified appropriately. The functional prototype was then put forward for clinical trials in collaboration with nearby hospitals.
- 6 **Development of Supporting Systems:** standard operating procedures were developed to ensure that the PoCT device was appropriately usable in the envisioned context. The design team also collaborated with doctors to outline specific services for the device and training programs needed for the skill building of technicians. Designers also conceptualised the databases and backend systems needed for recording and displaying diagnostic data. Since the designed concept was modular, auxiliary devices such as printers could be conceptualised. Unfortunately, the project timeline could not permit the implementation and testing of such components of the solution.

Section N.2 in **Appendix N** Shows several images of various stages in the development process. Figures 3.3 and 3.4 below show the context and the final designed solution.

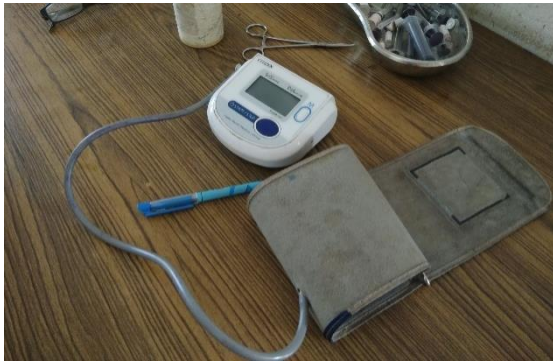


Figure 3.3: A digital blood pressure monitor in a PHC.

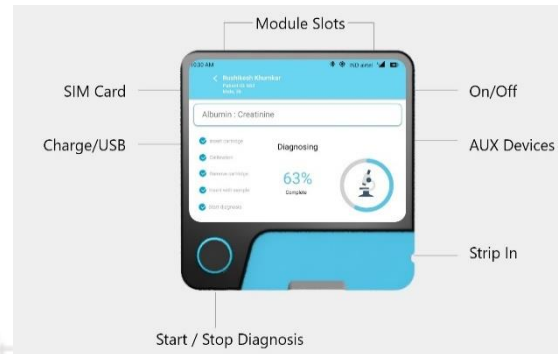


Figure 3.4: The user interface and details of the PoCT device concept.

3.3.2 Retrospective Analysis of the Project

Overall, the outcomes of the project have been a success. Since completing the product design, the team has received funding for developing a marketable solution and formed a startup around the goal. Still, from the perspective of holistic frugal design, there were some shortcomings to the design process.

The design research for the project focused on understanding the environment and infrastructure of the PHCs. Although there were several interviews with the personnel on location, an in-depth understanding of their daily work practices could have uncovered more detailed insights. The team only realised this when creating design iterations and testing the concept.

Another limitation of the project was in execution of the co-design approach. A few co-design sessions were conducted during the design research phase; however, these did not yield notable results. The design project involved collaborators, project initiators, and PHC personnel for concept evaluation. Participants could not directly contribute to idea generation and development due to the technical nature of the product. Co-design activities were also not conducted for developing the strategic aspects of the solution. Due to this, the supporting services were conceived using traditional ideation methods and towards the end of the project timeline.

The technical nature of the project meant that there were some limitations for designers in developing multiple fully functional prototypes within the project timeline. Therefore, technically intensive frugal design projects must be allotted adequate time and resources for functional prototype development and testing. Such projects may also need the development of 'allied products' that support the main solution. Similarly, it is essential to conceive supporting services and systems to ensure the solution works efficiently.

Towards the end of this project, the team also envisioned data gathering, organisation, and presentation methods for the PoCT device. Such aspects were not part of the initial concept but grew from iterative testing and refinement. These emergent requirements partially shifted the focus of product development from pure product development to systems design midway in the project. Although this was necessary for the project, an effective frugal design approach may have

highlighted the need for holistic design at early design phases, thus saving precious development time.

In summary, the design process's main shortcomings were a lack of co-design process during idea generation and development, technical limitations in developing multiple functional prototypes, and not considering a holistic solution at early design phases.

Other outcomes of the retrospective analysis of this project are summarised in the table below:

Table 3.2: Summary of retrospective analysis of the project: Designing Point of Care Testing Device for PHCs.

Key design guidelines	Activities Conducted in the project	Limitations of the project activities
Designers must gain a deep and a holistic understanding of the context	Observational studies of work practices, Interviews with PHC personnel and multiple field visits to different locations were conducted.	There were some limitations in gaining a deep understanding of the daily lives of the PHC personnel due to the unavailability of appropriate frameworks.
Designers must gain a deep understanding of the primary user's daily lives	Observational studies of work environments and interviews with PHC personnel were conducted	In retrospect, the designers were unsure of the depth to which the user's daily lives needed to be assessed.
Design stages must be implemented using a co-design approach	Participatory understanding of context and evaluation of concepts were done, but Co-design activities for ideation and design development were not done.	Designers used traditional idea generation methods in the absence of specific participatory tools.
Products must fulfil the need and be reliable in performance	CAD models were developed and analysed. Functional prototypes were used for testing in a clinical setting.	Specific reliability engineering methods were not implemented.
Designers must assess existing infrastructure	Existing infrastructure in the context was analysed through field visits	The context was analysed through observational studies. The project lacked co-design approaches for ideation and concept generation.
Designers must integrate income-generating opportunities	Specific business models and income generation activities were not developed. However, training programs were conceived to support users.	The development of business models and value chains was not considered during the project.
Designers must integrate various community and skill development activities	Design research and analysis were done in collaboration with stakeholders, but co-design activities were not conducted during ideation and concept generation.	Concept generation and development followed a typical process. Specific tools were not available for participatory concept generation in such contexts.

Designers must conceive of appropriate services to provide with the product	Some services, training programs and supporting products were developed as part of the project.	Services were not detailed during the concept development phase since the focus was on product design. Pilot tests for services were not conducted due to limited project scope.
Designers must create appropriate and novel means of creating awareness	Training programs were considered as avenues for creating awareness. Specific marketing and dissemination methods were not developed.	Activities related to marketing, advertisement and dissemination were not considered within the project scope.
Designers must assess the solution's performance	The solution was iteratively evaluated during product development and UI testing. However, an impact assessment of the solution was not done.	Product was only assessed in technical parameters using established methods. The impact assessment was not considered within the project scope.

3.3.2.1 Project Challenges and Constraints

Unlike other projects reviewed here, this one used high-end technology as a working principle. The major constraints faced in this project were related to access to resources and production facilities. Since the product was state-of-the-art, it needed specialised materials and manufacturing processes, which were difficult to find within the development vicinity.

The skill and literacy of the users presented another significant constraint during the development. The product design had to consider alternatives that mitigated these constraints effectively. For example, prototyping was done in house using desktop prototyping methods as far as possible. The UI design was optimised to align with mobile phone apps to make the product easier to learn and operate.

There were also constraints in conducting effective co-design activities in the project. Since the design team worked with multiple PHCs, a specific set of stakeholders were not part of the project throughout. Due to this, participatory ideation and concept generation were not effectively done. Therefore, it is important to include the same stakeholders throughout the process as far as possible for an effective frugal design approach.

The retrospective analysis shows the importance of defining the project scope at the initial stages. For effectively implementing the guidelines, the project scope must include impact assessment and testing of the systems supporting the solution.

3.4 Project 3: Design of Ginger & Turmeric Washing Machine

The design team wanted to intervene in scale-appropriate agricultural machinery for Northeast India in this project. The mainstream agricultural industry has long neglected this machinery segment, especially in MCs in the Northeast. Scale-appropriate agricultural machinery can bring economies of scale into the backyards of the region's small farmers and improve their income [14]. Scale appropriate farm equipment can also change sustenance based agricultural practices into commercially viable agriculture [15].

3.4.1 Project Brief and Design process

The project was funded through a government grant (Design Innovation Centre), and the author, with three other co-investigators, was involved in the equipment's design and development. Ginger and turmeric were selected for this intervention since these are commonly grown produce in small-sized farms. Also, nearly 57% of ginger is harvested in the Northeast, and some locations produce an elusive and famous variety of ginger [16].

In current practice, farmers ship uncleaned produce to nearby markets where they are cleaned. Due to this, a large part of their freight weight consists of waste, and they do not get a good wage on their products since it is perceived to be of lower quality. Having appropriate machines that the farmers can use and maintain would better the quality of their products and encourage further technology adoption [14]. Although Large-scale machines are available in the market, they are not viable for small scale farmers. On the other hand, small scale machines are not necessarily designed with the marginal farmer in mind. Therefore, the designers thought it was pertinent to develop an appropriate product focusing on the problems faced by the small-land-holding farmers in the MCs. The design team envisioned a sustainable and affordable solution that the farmer found easy to operate and maintain.

The outline of the design process followed in the project is shown below:

- 1 **Problem understanding:** The project started with secondary research where the design team studied the farming process for ginger and turmeric. Existing solutions for post-harvest processing were identified and analysed. The team also conducted expert interviews to understand the fundamental process of agricultural machinery design, harvesting and requirements specific to the Northeast. With the help of experts, the team identified farmers and locations for further detailed research. The team also clarified the design brief and identified aspects that needed deeper research and understanding.
- 2 **Understanding the Context and Users:** The second phase focused on in-depth design research. The team conducted field visits to several locations and interviewed people from various avenues. During the field visits, the design team conducted observational studies of the context, interviewed the farmers, experts and government stakeholders. Multiple field visits, observational studies and interviews were conducted throughout the development process.

- 3 **Analysis of Research:** Data gathered from multiple field visits and interviews were analysed to identify specific design insights, opportunities for product development and user needs. The analysis resulted in several design directions, which were then evaluated based on potential impact and practicality in development. The open-ended design research enabled redefining the design brief and identifying the scope for multiple design interventions. Two specific directions were selected for further exploration. Firstly, the team identified the need for a machine to wash ginger and turmeric post-harvesting. No such scale appropriate devices were available in the market. Second, the farmers needed a means for boiling turmeric post-harvest. Boiling is the secondary processing of turmeric that locks in the flavours and makes the product suitable for commercial applications. Currently, the farmers burnt biomass to heat large cauldrons of water where the turmeric was boiled. Research suggested that steaming the turmeric was a better process since it required less fuel and water [17]. Therefore, the design team formulated an additional design brief to explore the design of a small-scale turmeric steaming machine.
- 4 **Ideation and Concept Generation:** After the design briefs were finalised, the team conducted multiple idea generation sessions to develop a database of possible solutions. These idea generation sessions varied from traditional brainstorming between team members to collaborative ideation sessions between students. Students were given insights gathered from the design research in the collaborative sessions and asked to develop appropriate solutions using various methods. The design team also conducted a literature search by identifying patents, processes and working principles.
- 5 **Product Architecture Development:** The design team collated and evaluated the concepts generated from the extensive ideation sessions. A set of concepts was combined to create the final concept for the design briefs. The team then developed multiple prototypes for each brief and evaluated them on technical parameters. Various 'jugaad prototypes' were created to explore the effectiveness of different working principles. Multiple working principles were explored during development, including ultrasonic cleaning, agitation and vibration of the ginger. Simultaneously a CAD model for the ginger/turmeric washing machine was developed with detailed embodiment and a focus on modular product architecture. Finally, the design team focused on developing the washing machine in detail due to time constraints in the project.
- 6 **Prototyping:** Prototyping of the product followed a unique collaborative process. An award-winning grassroots innovator was enlisted to develop the final functional product prototype. This collaboration enabled the rethinking of product manufacturing by using off-the-shelf and easily accessible parts to construct the product. For example, a part of the ginger washing machine needed a large gear that was difficult to manufacture. Gear assembly was cleverly replaced with a bicycle and castor wheel parts. Collaboration with grassroots innovators for prototyping thus reduced product cost significantly.
- 7 **Systems Design:** After testing the prototype for its effectiveness, the design team focused on developing holistic aspects of the solution. The team ideated specific models for services, business and dissemination of the product. Several iterations were done to the final product concept when ideating such strategic aspects of the solution. The team envisioned a PSS model where multiple farmers could own and share the product. This insight meant that the product needed to be transported between different farms when in use. Based on this, the product was modified to be mounted on a small goods carrier.

Overall the project achieved the initial goals and design brief; however, extensive testing of the product remains to be done.

Section N.3 in **Appendix N** Shows several images of various stages in the development process. Figures 3.5 and 3.6 below show the context and the final designed solution:



Figure 3.5: The design team with collaborators.



Figure 3.6: Final prototype of the washing machine.

3.4.2 Retrospective Analysis of the Project

The strength of the design process followed in this project was in the user research and prototyping. Although the initial brief had determined the project scope, the team still focused on identifying new product opportunities that were not highlighted. Multiple field visits and observational studies were conducted to reaffirm assumptions in the initial brief. Several unique design insights, requirements and opportunities could be identified due to the extensive research.

‘jugaad prototyping’ was used for developing the product architecture and embodiment. The focus of prototyping exercises was to develop low-cost models with which the working principle of the solution could be extensively tested. Off the shelf components and repurposed parts were used when developing the ‘jugaad prototypes’, which led the team to embody low cost and modular product architectures. Additionally, the team collaborated with grassroots innovators for prototyping, thus infusing the project with the frugal mindset needed to reduce production costs significantly.

Refining the design brief and multiple design research sessions also helped identify new design opportunities. The need for a turmeric steamer for post-processing the produce was identified and a concept was developed using ‘jugaad prototypes’ to test multiple working principles. Eventually, however, the focus shifted toward developing the washing machine and kept the steamer design as future work in the project.

Extensive design research also highlighted the need for system design approaches to disseminate the product. The team developed PSS models and services to support the final concept. The PSS models developed included some strategies for recovering costs for product maintenance and upkeep. A modified version of the PSS model was also developed to enable income opportunities.

Still, there were some shortcomings to the process followed when considering the overall frugal design guidelines.

The major shortcoming was that the team did not conduct collaborative idea generation and evaluation with the intended users of the products. Participatory ideation and concept generation were mostly conducted with students and researchers. Concept evaluations were also based on technical parameters. The aspects were also not pilot-tested since they were not considered within the scope of the project brief. A summary of the project's retrospective analysis is shown in Table 3.7:

Table 3.3: Summary of retrospective analysis of the project: Design of Ginger/Turmeric Washing Machine

Key design guidelines	Activities Conducted in the project	Limitations of the project activities
Designers must gain a deep and a holistic understanding of the context	Designers conducted interviews and contextual observations for identifying design opportunities and insights. Multiple field visits were conducted throughout the project.	The process was extensive and adequate. However, the team felt the need for a framework for supporting the design research.
Designers must gain a deep understanding of the primary user's daily lives	Field visits helped understand the farming practices and interviews with farmers helped understand their daily lives.	The work was considered adequate. Several design insights and opportunities were identified.
Design stages must be implemented using a co-design approach	Participatory approaches were used during design research. Co-design activities for concept generation and evaluation were conducted internally.	Specific co-creation activities for concept generation and user evaluation were not conducted due to the unavailability of specific frameworks.
Products must fulfil the need and be reliable in performance	'Jugaad prototyping' was used to test and develop the product architecture and embodiment iteratively.	'Jugaad prototyping' enabled the testing of working principles on technical parameters only. The final product was not extensively tested on the field. Specific reliability engineering methods were not used in testing.
Designers must assess existing infrastructure	Existing infrastructure in the context was analysed through multiple field visits	The research work done was considered adequate.
Designers must integrate income-generating opportunities	A supporting PSS model was conceived, which considered means for generating revenue for product maintenance and upkeep.	Only an initial version of the PSS model was developed. The model only considered means for offsetting maintenance costs and did not have extensive income-generating opportunities.

Designers must integrate various community and skill development activities	Such activities were not considered within the project scope. However, the PSS model conceive contained some dissemination strategies.	Specific skill development activities for the community were not considered in the project scope.
Designers must conceive of appropriate services to provide with the product	Supportive services and cost-offsetting strategies for the maintenance and upkeep of the product were conceived as part of PSS.	Pilot tests were not conducted due to limited project scope. PSS models were not detailed and evaluated due to a lack of appropriate frameworks.
Designers must create appropriate and novel means of creating awareness	Some specific dissemination activities as part of the PSS model were created.	Detailed strategies for dissemination, marketing and advertising were not considered within the project scope.
Designers must assess the solution's performance	Jugaad prototyping helped to assess the product performance iteratively. However, evaluation of the holistic solution, including the PSS model, was not done.	Product was only assessed in technical parameters. PSS models were not verified through testing, and an impact assessment was not considered within the project scope.

3.4.2.1 Project Challenges and Constraints

One of the major challenges was the lack of technical information about designing low-cost and appropriate mechanised solutions for the northeast Indian context. Although enough technical information is available to design farm equipment, specific guidelines for agricultural technology for MC were limited. The geographical and environmental aspects of the context also had a large impact on agricultural machinery, affecting transport and usage. For example, the remoteness of the locations meant that there was limited access to the grid or fuels to run the machines. Availability of spare parts and mechanics at such remote locations also hinders solutions with a complex mechanism or those that cannot be easily transported.

Social networks play a huge role in the adoption of farm mechanisation in MC. Interviews with farmers in the MC highlighted that they tend to learn from one another. They are apprehensive of using machines that others are not using. Therefore, the scope of a product design goes beyond the product embodiment, and appropriate services for dissemination are needed for the product's success. Although a PSS model was conceived for this purpose, since they were developed after the product concept, several iterations and modifications of the embodiment were needed to support such aspects. This experience emphasised that strategic design needs must be simultaneously considered with the product embodiment and architecture design in a frugal design process.

3.5 Project 4: Design of a Low-cost Bicycle Trolley for Washermen

In India, the community of people who wash clothes for households and institutions are commonly called 'Dhobis'. Before the Indian independence, Dhobis were considered 'untouchables' and belonged to lower castes in the social hierarchy[18]. Over time the social stigma of Casteism has reduced, and the Dhobis are now seen as a professional community of service providers.

Nonetheless, the community faces many issues such as poverty, inequality and literacy[19]. Majority of people who work as Dhobis belong to minority and underprivileged sections of society. They struggle to earn a living due to the low revenue, strenuous work and difficult living conditions. Their working methods are inherited, and they have been following the same methods for many generations[19].

Despite a large population involved in the profession, Dhobis are an under-explored user group from a design perspective. The problem is that most of the products for washing clothes are not designed for the user group or the context in which they work. Clothes washing products common in the Indian household are not quite common in the Dhobi community. The team believed that this gap was due to an inadequate understanding of the community's needs and argued that appropriate research could bridge the gap. Thus, the team convened that appropriate design interventions can benefit the community and their work practices.

3.5.1 Project Brief and Design Process

The goal of this project was formulated as 'to understand the needs and requirements of the Dhobi community in Guwahati, Assam and design appropriate solutions to help them in their work'. It was a collaborative project undertaken jointly by Procter and Gamble (P&G) Research, Brussels and Department of Design (DoD), Indian Institute of Technology Guwahati (IITG). The vision was to design novel solutions of mutual interest to P&G and DoD. The author worked as a co-investigator and supervisor in the project.

The project was done in two parts; in the first part, a team of researchers examined the work practices and daily lives of the Dhobi community in Guwahati. With this, several design directions were identified. Some of these directions were explored and collaboratively shortlisted by the project stakeholders. In the next part of the project, the product was designed, developed and evaluated. Overall the following design process was followed for the project:

- 1 **Context analysis:** The project started with discussing the client brief and understanding the mutual project goals. The project plan was collaboratively created with the clients. The design team then conducted multiple field visits and extensively studied the MC from various perspectives. This study uncovered two types of work practices: Structured and Unstructured. Dhobis, who practised structured work practices, were typically employed by a business and had access to machines, and the scenario could not be considered an MC. The Unstructured group of Dhobis, on the other hand, typically worked alone or in groups of two or three. They did not own permanent shops and used river banks to wash their clothes. The design team focused on identifying the needs of the unstructured group

for a design intervention. The team conducted observational studies, unstructured interviews and audio-video documentation as part of context analysis.

- 2 **Understanding Daily Lives and Work Practices:** In the second phase of the research, the design team delved deeper into understanding the daily lives of the Unstructured group of Dhobis. The team conducted multiple field visits and interviewed the people in their work environments. Furthermore, the team also conducted participatory sessions with the people to understand their work practices better. Through this research, the team identified specific insights, design opportunities and important needs of the people.
- 3 **Analysis of Research:** The design team then spent a significant amount of time making sense of the collected data. Several approaches were used to analyse research, including design-oriented methods such as affinity mapping [20], value chain analysis [21] and grounded theory methods[22]. Multiple project briefs were developed and collaboratively evaluated with the clients, users, and the design team to choose the design directions. Initial ideas for the chosen design directions were then developed to facilitate discussions and decision making. Part one of the project concluded with a mutual agreement on a design brief for further development. The chosen direction was to design and develop a carrier for transporting bundles of clothes to and from the river banks where the Dhobis worked.
- 4 **Collaborative Ideation:** The design team generated multiple concepts for the chosen design direction. Typical idea generation methods such as brainstorming, scamper, 6-3-5 method were used. Co-design sessions with the users were also attempted during concept generation. Unfortunately, the results of the co-design exercises were not fruitful due to multiple challenges faced in executing the sessions in MC. Product concepts that could solve multiple problems in the context and fulfil the selected brief were developed further.
- 5 **Collaborative Selection of Concepts:** The design concept was developed iteratively. First, mockups were created to understand the scale and effectiveness of the solution. Next, several full-scale prototypes were created and tested for performance. The outcomes of these in-house testing were discussed with the stakeholders (clients, supervisors and users). These co-evaluative sessions provided multiple avenues for improving the concept and solving related problems identified in prior research. A prototype version was selected, and several new design opportunities for its upgrade were also identified.
- 6 **Product Development:** After receiving the go-ahead, the embodiment and modular architecture for the product were created. Simple manufacturing processes of bending and fabrication were chosen to minimise the product cost. In addition, a PSS model and specific dissemination methods were conceived to support the product. A unique strategy was also derived for branding the product and provided clients with scope for advertising. The team also developed systems models for supporting the product in use, its services and its distribution. The final design was evaluated with the users and found suitable for their work. The project concluded with the demonstration of the solution to the client and stakeholders. Unfortunately, the project scope did not allow pilot testing, implementation, and impact measurement.

Section N.4 in **Appendix N** Shows some images of the product development process. Figures 3.7 shows the context and the final designed solution in a promotional render created.

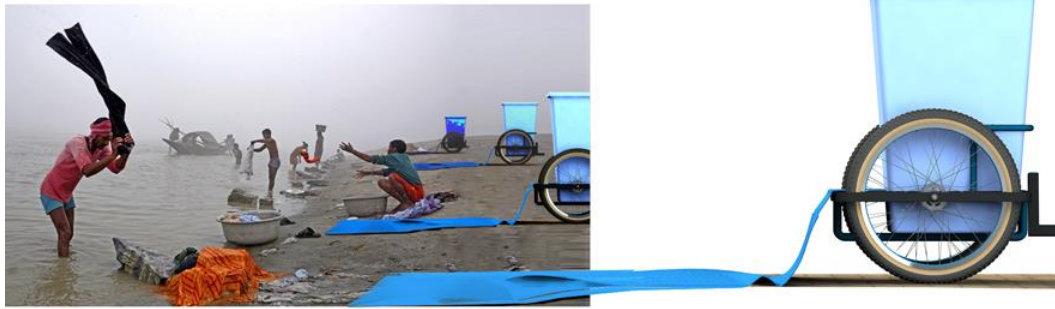


Figure 3.7: Rendering of the final product showing its use in context.

The project outcomes could effectively meet the overall goals laid out in the design brief. The final product solved a pertinent need of the selected user group, and the design was of mutual interest to the initiators. The designers also devised strategic aspects of the solutions, such as supporting the PSS model, which would help disseminate the product. Additional services for maintaining the product and financial aids for its purchase were also devised.

3.5.2 Retrospective Analysis of the Project

The retrospective analysis highlighted how the otherwise successful project deviated from the design guidelines. Primarily, the project's scope was not broad enough to consider extensive pilot testing of the solution. Due to this, it could not be understood if the solution would affect people's work practices in the long term. Moreover, the holistic components of the solution, such as attached services and other PSS components, could not be evaluated effectively due to limited project scope.

Furthermore, the development of the prototype was done in-house, which restricted the teams understanding of manufacturability and production. Due to this, the downstream planning of the product's dissemination was not part of the project.

The project highlighted the design considerations at the trailing end of a frugal design process. The criteria for completing a frugal design process should include a pilot demonstration and planning for production and scaling. Such criteria should also be included in the client agreements and briefs if possible.

Other findings from the retrospective analysis are summarised in the table below:

Table 3.4: Summary of retrospective analysis of the project: Design of Low-cost Bicycle Trolley for Washermen.

Key design guidelines	Activities Conducted in the project	Limitations of the project activities
Designers must gain a deep and a holistic understanding of the context	Multiple field visits to river banks, homes of Dhobis and other related places were conducted. Designers conducted interviews and contextual observations for identifying design opportunities and insights.	The process was extensive and adequate. However, a structured framework for conducting the studies would have been helpful.

Designers must gain a deep understanding of the primary user's daily lives	The designer understood the work practices in location and interviewed the people to understand their daily lives.	The work was adequate. Significant insights and design opportunities were derived.
Design stages must be implemented using a co-design approach	Participatory approaches were used for gaining user understanding, idea generation and selection.	Language barriers and power differences with the user-created hindrances in effective participatory ideation.
Products must fulfil the need and be reliable in performance	The product was iteratively prototyped. Multiple prototypes were created and tested. Extensive reliability testing of the final solution was not done.	Although specific reliability engineering methods were not implemented, multiple product iterations ensured reliability. However, the final solution was not extensively tested on the field.
Designers must assess existing infrastructure	Existing infrastructure in the context was analysed through multiple field visits	The research work done was adequate.
Designers must integrate income-generating opportunities	Specific income generation activities were not developed. However, a supporting PSS model was conceived.	The development of income generation was not considered within the project scope.
Designers must integrate various community and skill development activities	Such activities were not considered within the project scope.	Co-Design activities were limited to research, ideation and concept selection. Specific skill development activities for the community were not considered in the project scope.
Designers must conceive of appropriate services to provide with the product	Some supportive services for the maintenance and upkeep of the product were conceived.	Pilot tests for services were not conducted due to limited project scope. Services were not detailed.
Designers must create appropriate and novel means of creating awareness	Novel means of advertising through local shops frequented by Dhobis was conceived.	Some novel strategies for creating awareness were devised, but these were not tested.
Designers must assess the solution's performance	The product's performance was evaluated through iterative prototyping. However, evaluation of the holistic solution through pilot tests was not done.	Product was only assessed in technical parameters using established methods. An impact assessment was not considered within the project scope.

3.5.2.1 Project Challenges and Constraints

Since the users were strapped for time, they found it difficult to engage at length in research and co-design activities. Although participants were compensated for their time, they were still reluctant to leave their work. The team also saw power differences among different user groups (superiors, foremen and subordinates). Due to this, co-design activities did not instigate too many

counterpoints and alternative ideas. Power differences were also felt between the design team and the user due to social class. The design team tried to mitigate such issues through prolonged communication with some users throughout the project timeline. Finally, since the users were unfamiliar with the design process, they found difficulty presenting novel ideas and being non-judgemental.

The other constraint that restricted a better frugal design was the project scope. Although the team met the client brief and delivered on their promises, in retrospect, significant work remained. The service, business and dissemination models which were developed were not part of the project's initial scope, due to which they were not effectively tested or detailed. Had systems design been considered in detail, specific interventions could be devised for income generation and engaging users in the value chain. Therefore, in an effective frugal design process, it is important to detail the service, business and dissemination models as much as the product design.

One of the critical learnings from this project was the need for two specific types of research in frugal design projects. The first type is where design research focuses on the context and its effect on the people. The second type is where the focus is specifically on the users, their lives and practices. Delineating these two types of research activities highlights the specific nature and depth of design research required for a frugal design process.

Another insight was that ambiguity in identifying the right solution affects the design process positively. In this project, since the team initially did not have clarity on the right product to design, significant time was spent on design research, which enabled a greater understanding of the context and user requirements. Knowing the specific product to design would have biased the design research to focus only on aspects perceived as important. Therefore, it is important to redefine a project brief even when the client's brief is exact.

3.6 Discussion

The retrospective analysis presented in this chapter adds to the understanding of frugal design and takes us one step closer to defining a systematic approach. The objective here was to understand the challenges and constraints in implementing a design process in MC, and in the process, outline the characteristics of an effective frugal design approach.

The outcomes indicate that frugal design, especially 'frugality,' highly depends on the product architecture design. It affects the cost and manufacturing of the product and aspects such as maintenance, consumable resources, upgradeability, and end-of-life considerations. These, in turn, affect how systems, services, and dissemination strategies are envisioned. Therefore, product design and strategic design aspects in an effective solution for MC are closely interlinked.

To define such interlinked holistic concepts resulting from a frugal design process, a new construct called '**Solution Proposal**' is proposed as follows:

A 'Solution proposal' is a detailed plan that describes the services, business models, dissemination activities, and auxiliary products needed to effectively implement a 'product design concept' in an MC to meet the user needs sustainably.

A 'product design concept' is a detailed plan for creating a tangible artefact that describes how it looks, feels, functions, is manufactured and is used.

Defining the 'Solution Proposal' construct allows us to demarcate the boundary and scope of a frugal design process. Thus, an effective frugal design process ends with creating a Product Design Concept and a Solution Proposal.

3.6.1 Constraints that Affect Frugal Design

In the context of this research, constraints are defined as aspects of the design context that inhibit designers in executing any design process as intended. Designers may encounter two types of constraints in a design project in MC [23]. The first type is a set of generalisable constraints common for all MC, and the second are constraints that specifically relate to the product or service being designed. All constraints must be effectively mitigated by modifying the process or designing appropriate features in the overall solution. Alternatively, designers could leverage these constraints through clever ideas. The retrospective analysis indicated four groups of constraints exist in MCs which affect the design process. These are:

- 1 Environmental and Social Constraints:** Typically, environmental constraints originate from remoteness, terrain, and weather conditions in the context. On the other hand, social constraints result from language, social networks, structures, and practices in a context. Some environmental constraints were encountered in the projects, which were effectively mitigated by modifying the solution. For example, the final product designs were modified to work in the rugged terrain and environmental conditions in the ginger/turmeric washing machine and bicycle carrier projects. Similarly, social constraints related to language barriers and power differences were encountered in the bicycle carrier project, which inhibited the effective engagement of the people in participatory design and ideation exercises.
- 2 Socio-Political and Legal Constraints:** Socio-Political constraints are related to the political beliefs, relationships, and social arrangements among the people in the context. Legal constraints are related to protecting rights, property, safety, and law and order. Several socio-political constraints were encountered in the ginger/turmeric washing machine project, where if a farmer wanted to utilise certain equipment, he needed support from the community. Similarly, the vending platform design project uncovered unofficial hierarchies and agents coordinating the market.
- 3 Production and Infrastructure Constraints:** The next group of constraints identified was related to access to materials, manufacturing processes, skilled labour, and infrastructure. In the ginger/turmeric washing machine, designers could not consider developing solutions that depended heavily on continuous electricity supply. Many high-tech working principles were discarded due to this. Similarly, in the PoCT design project, there was difficulty finding skilled labour and infrastructure to develop the devices. Knowledgeable manufacturers for developing the devices were rare in the vicinity, even for relatively well-known processes such as injection moulding and die casting.

- 4 Individual Level Constraints:** Some identified constraints were related to the individuals in the context, which inadvertently affected the design process and the solution output. Such constraints arose from people's lack of specialised skills, vocation, literacy, affordability and wellbeing. These constraints were specifically faced when developing the bicycle carriers and PoCT devices. Designers could not effectively conduct co-design ideation sessions with users since they did not understand the project goals. Also, participants in the co-design session could not build on each other ideas and presented only a few counter-arguments to progress the session. Similarly, users working in PHCs lacked good technical know-how and had less time to conduct diagnostic tests with elaborate operating procedures. This constraint prohibited the designers from conceiving solutions with high skill requirements.

A pre-emptive knowledge of constraints offered by MC can help designers focus their design efforts. Designers can develop concepts that inherently mitigate such constraints or devise specific strategies for circumventing them through certain processes. The constraints could be used as frameworks for directing design research and understanding the context in more detail. Designers can, for example, conduct research activities to clarify the root causes of these constraints, thus identifying ideas for mitigating them [24].

3.6.2 General Requirements for a Frugal Design Approach

Each subsection below discusses a group of unique requirements for systematically developing holistic and frugal solutions for MC. These requirements were derived from a critical assessment of insights from the retrospective analysis study, analysis of existing case examples and the extant literature review.

3.6.2.1 Project Scope and Time Frame

A Project's scope is defined by the end goals and the planned outcomes. In typical design processes, the end goals of a project are limited to the demonstration and testing of a new product concept. Retrospective analysis results indicated that even projects with low complexity architecture needed significant consideration of strategic aspects in MC such as service, business, dissemination and income generation (i.e. the solution proposal).

Therefore, the project scope needs to be broadened to consider outcomes such as testing the solution proposal and planning for impact assessment and scaling up. A Frugal design process thus ends with a detailed plan for product development and an evaluation of the solution proposal. Consequently, when planning a frugal design project, the end goals and outcomes must be clearly defined and measurable.

In typical scenarios, designers are sometimes presented with briefs that specify the exact solution to be designed. Even when engaging with such a structured brief, designers in MC must broaden the project scope to align with the outcomes of a frugal design process. Therefore, a frugal design process needs a distinct phase where the design brief is reinterpreted and redefined.

Obviously, there are some caveats in broadening the project scope. Most importantly, the time for the project may increase. Therefore, during the initial stages of a Frugal design process, it is

important to plan and approve the project's timeline, milestones, and outcomes. The retrospective analysis also highlighted that the design research phase is crucial for frugal design. Thus, a significant amount of project time may be needed to understand the MC. Also, a technically complex project may need additional time for evaluating the working principles and iterative concept development.

Still, Limiting the project scope to accommodate a timeline is not recommended as designers may neglect effectively developing essential aspects of the solution proposal.

In summary, the requirements related to the scope of a frugal design approach are as follows:

- A frugal design approach must have a broadened scope to include design, development and testing of the Solution Proposal
- Designers must be able to clearly define the end goal and the outcome in a frugal design approach. The approach should provide a means to define criteria for project success.
- Ideally, the outcome of a frugal design approach should be a detailed plan of the deployment, impact assessment, and scaling up of the product design and the solution proposal.
- The frugal design approach must accommodate redefining and reinterpreting the initial design brief to broaden the project scope.
- One of the first steps of an effective frugal design approach should be planning to accommodate the broadened scope.

3.6.2.2 *Two Types of Research Activities*

The retrospective analysis uncovered two types of design research activities needed in a frugal design project. The first type is where the designers focus on understanding the MC itself, and the second is where they focus on understanding the users' lives. Both types of research are uniquely different and essential for effectively implementing a frugal design approach.

Design research needed for understanding MC focuses on uncovering specific information about the context, its surroundings, important stakeholders, infrastructure and supporting agencies. Such research can be primarily done through field visits, observational studies and interviews with agents in the context.

During field visits, designers can try to uncover the specific aspects of the MC and gain a first-hand experience of the lives of all people within a 'context boundary'. A context boundary can be defined as a geographical area and the span of social networks which a holistic solution will affect. In design research activities focused on understanding MC, designers must observe the socio-technical actions performed within the context boundary that affect the overall implementation of a planned solution.

A clearer understanding of the MC can also be gained by interviewing key persons and agencies in the context. These persons and agencies may not be the typical users or the direct beneficiaries of the solution's value chain. For example, social and political leaders, government officers, and NGO operatives in the context can provide indispensable insights into the MC. Such stakeholders can be called 'visionaries' and are typically driven by a motivation of social upliftment of the people in the context. Apart from the visionaries, designers can also interview key persons from agencies that provide infrastructure and financial support to people in the context. For an effective frugal design

process, it is important to include such stakeholders and visionaries in the design process and engage them in relevant co-design activities.

The second type of design research needed for an effective frugal design approach is gaining a deep understanding of the lives and work practices of the direct users of the solution. Designers can use methods such as Interviews, Focus groups[25, p. 51], shadowing [26, p. 26], card sorting[27], participatory approaches[28] for this purpose. This type of research intends to identify the exact user needs and clearly understand the solution's short- and long-term effects on their lives.

These two distinct design research activities help establish the needs and requirements, redefine the project brief, identify new design opportunities, and establish a holistic solution's scope.

Following typical NPD processes may restrict the designers in conducting such multi-objective and multi-staged research activities if only certain methods are favoured. Therefore, an effective frugal design approach needs to include these distinct research phases into the process explicitly. Such an explicit inclusion will ensure that designers prioritise in-depth design research in MC even when designing products with low embodiment complexity, therefore improving the effectiveness of the solution proposal.

In summary, the requirements related to design research in a frugal design approach are as follows:

- A frugal design approach must have two distinct phases in conducting design research. In the first phase, the details of MC must be understood clearly, and in the second phase, the users' daily lives must be studied.
- The approach must encourage designers to execute both research phases even when product embodiment complexity is low.
- Designers must interview visionaries, stakeholders, and users to adequately understand the context.
- Selected visionaries, stakeholders and users should be included throughout the project using participatory activities.

3.6.2.3 Redefining the Project Brief

Redefining a project brief is a crucial step in a frugal design process. In a typical scenario, designers may base their solutions on the initial brief provided by the clients or project initiators. However, this initial brief may not cover the users' true needs in the context since a clear understanding has not been established at the time. Thus, a distinct phase of the frugal design approach must include a redefinition of the project brief and record new design opportunities in the context.

The outcomes of the two-phase design research can also help identify such new design opportunities and redefine the project brief.

The retrospective analysis found that ambiguity on a solution positively affected the research process. When designers have no clear idea of what solution to design, they conduct extensive research, thus identifying potentially radical and appropriate interventions. Unfortunately, a specific design brief with a clear solution type restricts the designer's motivation to conduct broad research. Therefore, a distinct phase in a frugal design approach should force the designers to redefine the design brief, thus imparting partial ambiguity into the design process.

In summary, the requirements for a frugal design approach related to redefining the project brief are:

- A frugal design approach must have a stage for redefining the project brief.
- The analysis of the two-phase research outcomes must result in a reformulated design brief.

3.6.2.4 Co-Design and Collaboration

Numerous guidelines for frugal design in MC indicate that collaboration and co-design must be considered foundational and indispensable to the process. The retrospective analysis of projects strengthened this argument even further.

Outcomes of the projects where collaborations and co-design were rigorously explored were significantly better. Co-design approaches helped designers implement various frugal design guidelines better and led to better solutions.

The retrospective analysis also indicated a need for multiple co-design sessions during a frugal design process. Three distinct co-design activities are outlined for a frugal design approach in MC:

- 1 **Participatory research activities** are needed for gaining a deep understanding of the context and daily lives of the users. Such activities can help identify tacit knowledge and information that is difficult to uncover through other methods.
- 2 **Co-Creative idea generation activities** are needed for developing appropriate ideas. Such activities ensure that solutions are easy to adopt by the users and acceptable within the socio-political landscape of the context.
- 3 **Co-Evaluation activities** are needed for understanding the effectiveness of a product concept and solution proposal. Such co-design activities support the concept selection process by engaging the users, stakeholders, and visionaries to assess the overall solution. Such participatory evaluations can also help users and stakeholders envision their roles in making the solution successful.

Although participatory activities are crucial to success, there are some constraints in implementing them which designers need to consider carefully.

People in MC may not know about the best practices in design. Due to this, there may be a significant gap in implementing certain methods in the context. To mitigate this, designers need to sufficiently tutor the participants on the goals of these design methods and other technical details.

Power differences and socio-political concerns may also affect how participants behave during co-design, affecting the session outcomes. Designers must take reasonable measures to mitigate such constraints when conducting participatory activities in MC.

Such constraints make it imperative to include steps of planning participatory activities and developing collaterals for effectively executing them in a frugal design approach for MC.

In summary, the requirements for a Frugal design Approach related to co-design and collaboration are as follows:

- A frugal design approach must accommodate identifying appropriate stakeholders with whom designers can collaborate throughout the project.
- A frugal design approach must have at least three distinct co-design activities of Participatory research, Co-Creative idea generation and Co-Evaluation.
- Designers must be able to plan the co-design activities and develop appropriate tools to support them.

3.6.2.5 Strategic Design Considerations

The retrospective analysis showed that in many cases, strategic aspects of the solution were considered after the completion of product development, which caused designers to pay less attention to the solution proposal. Furthermore, considering strategic aspects late in the project caused unnecessary design iterations warranting additional development time. Therefore, in an effective frugal design approach, strategic design aspects must be considered in the early phases of the process.

Furthermore, specific strategic aspects such as value chain configuration, end-of-life planning and income generation opportunities must be explicitly considered when developing holistic solutions. The retrospective analysis further highlighted that detailing the service, dissemination and business models is as important as detailing the product design.

It is important to detail the strategic design aspects along with the product embodiment and architecture design. This process ensures that design ideas that may impact strategic aspects and product embodiment are easily accommodated. For example, if the product needs a certain consumable item to function, appropriate service models can be designed to improve access to the item. Similarly, if certain service-system components such as pay per use are needed, product embodiment can be modified to include mechanisms to monitor the usage patterns.

In summary, the requirements for a frugal design approach related to strategic design considerations are as follows:

- In an effective frugal design approach, strategic design aspects must be considered early in the design process, together with product design ideation.
- Value chain configuration, end-of-life planning and income generation opportunities must be explicitly considered in a frugal design approach.
- Detailing strategic design aspects must be done along with detailing the product embodiment and architecture design

3.6.2.6 Testing and Evaluation

Extensive pilot testing and evaluation of the product in context were not part of the design brief in the projects analysed in this chapter. Although this may be due to the projects being done in an academic setting, it is important to remember that such evaluative phases are essential in an extensive frugal design process.

Therefore, an effective frugal design approach must include pilot testing and evaluation of the solution proposal within the project scope. The solution proposal can be evaluated using simulations, co-evaluative sessions, or mockups. Moreover, if there are established ways to

measure the performance of the solution proposal, proxy methods used in service and socio-technical system design evaluations [29] can be used.

Designers must also consider planning for the impact assessment when the solution is scaled up. Although such an impact assessment may not be practical during the design phase, measurable success criteria for the solution must still be set. One way to create these measurable criteria and plan the impact assessment early is to develop a 'theory of change' [30] for the solution. A theory of change can provide a vision of how the solution may impact the context in the short and long term, thus offering measurable criteria.

In summary, the requirements for a frugal design approach related to testing and evaluations are as follows:

- An effective frugal design approach must consider testing and evaluating the product concept and solution proposal within the design scope.
- The strategic aspects of the design must be evaluated as rigorously as the product is evaluated in performance parameters.
- In an effective frugal design approach, measurable success criteria and a plan for impact assessment of the solution must be clearly defined.

3.6.2.7 Tools, Methods and Frameworks

Besides a structured approach to design, the projects analysed highlighted the need for a specific framework to guide the design process. For example, in the PoCT and farm equipment design projects, although the research was considered adequate and resulted in commendable insights, designers went about the process more or less in an ad-hoc manner. Usually, one interaction and design activity snow-balled into planning other related activities. Such a process requires more time and its endpoints are not visible clearly. Thus, a framework for systematically planning and executing the process would help achieve research depth within a limited time frame.

The retrospective analysis also highlighted that engineering design methods for reducing product cost and improving product reliability must be deeply integrated into an effective design process. The projects primarily used iterative prototyping and testing methods for improving performance. Had such iterations been guided by Design failure modes and effect analysis (DFMEA), Design for manufacturing (DFM), Fault tree analysis (FTA) and other engineering design methods, the overall cost and reliability could be improved further. Additionally, the analysis found that 'jugaad' prototyping effectively ensured the reliability of the product and its working principles.

In addition to specific research and design support, designers felt a lack of tools to support co-design in MC. Specifically, co-design tools for participatory idea generation and evolution with the users, stakeholders, and visionaries were needed.

The study confirmed the assumption that a systematic framework for designing holistic frugal concepts for MC is indeed required. For example, designers working on the vegetable vending cart resorted to a typical design process that inhibited them from exploring strategic design aspects. Following a traditional design process, designers encountered a false sense of security which stopped them from exploring alternate and holistic ideas with system-level implications.

Such challenges may be more pronounced for novice designers, illustrating that novice designers stand to benefit the most from a structured approach to frugal design for MC. Expert designers can also greatly benefit from it if the approach is sufficiently flexible, where unique process paths can be chosen depending on the project requirements.

In summary, the requirements for a frugal design approach related to tools, methods and frameworks are as follows:

- An effective frugal design approach incorporates specific tools and frameworks for supporting the project's design research and co-design activities.
- Existing tools and methods for product design must be compatible with the frugal design approach.
- An effective frugal design approach is structured and flexible.

3.7 Conclusion

This chapter presented the outcomes of a retrospective analysis of design projects done for the MC. The goals were to uncover the requirements for an effective frugal design approach and uncover the constraints that affect the process. Four projects were analysed, where the researcher played an active role in designing and developing the solutions. Analysis of the projects resulted in a list of constraints and requirements for frugal design, detailed in the discussion section of the chapter.

Four distinct groups of constraints that affected the frugal design process were uncovered. These were related to Environmental and Social aspects, Socio-Political and Legal aspects, Production and Infrastructure aspects, and individual-level constraints. Similar work was discovered in the literature review, where Aranda-Jan et al. [23] list the factors that affect the design process of medical devices in MC. Results from the retrospective analysis match the literature but provide a more general categorisation applicable to most product types.

Another outcome of the retrospective analysis was a comprehensive list of requirements for an effective frugal design approach. Seven groups of requirements were outlined which dictate the features of an effective frugal design approach. These requirements form the foundation for developing a framework for systematically conceptualising holistic and frugal solutions for MC and is discussed in upcoming Chapters.

The requirements list for a frugal design approach provided some unique insights into the design process. Overall the requirement for two distinct types of design research activities was observed. Also, three types of co-design activities are needed for effective frugal design. Several unique stakeholder types were also identified who can effectively contribute to co-design appropriate solutions for MC. These insights illustrate the depth of various design activities needed to effectively execute a frugal design process.

The study outcomes also led to developing a unique construct of 'Solution Proposal', which defines the holistic concept that is the outcome of a frugal design process.

The next chapter utilises the findings from the research outcomes discussed so far to develop unique frameworks for systematically conceptualising holistic and frugal solutions for MC.

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Chapter 4 Frameworks for a Systematic Frugal Design Approach

The extant literature review presented in Chapter 1 illustrated a critical research gap in that few design approaches exist to support a systematic design for marginal contexts (MC). Outcomes of Chapters 2 and 3 similarly indicated a need for an effective systematic frugal design process. This chapter consolidates the outcomes from prior research to outline two novel frameworks to address this lacuna.

First, a critical review of the existing design approaches for MC is presented, highlighting their strengths and shortcomings. This review provides a benchmark for synthesising two novel frameworks for systematic concept generation and evaluation of solutions for MC.

The first framework is called the '**Frugal Design Conceptualisation**' (FDC) framework and outlines a methodological approach for developing holistic and frugal solutions for MC. The framework was synthesised from the insights derived from the literature review, case studies and the immersive project experience. Section 4.2 describe the FDC framework and its synthesis in detail.

Several constraints to the frugal design process have also been identified in prior research. The second framework synthesised the insights related to such constraints into the **Context Evaluation Hierarchy** (CEH) framework. The CEH framework was developed to effectively evaluate design concepts and facilitate research activities in a frugal design process. The CEH framework and methodology of its synthesis are discussed in section 4.3.

Discussion section 4.4 presents how FDC and CEH frameworks can be practically implemented, why they are suitable for design in MC and how they can be used to develop appropriate design supports. Finally, the conclusion of this chapter highlights some considerations for the practical implementation of proposed frameworks.

4.1 A Critical Review of Existing Design Approaches

A recent literature review shows that the focus of scholarship on frugal design and innovation has been on understanding its characteristics and adequately defining the phenomenon [1]. Still, there is a growing interest in identifying practical approaches [1]. Pisoni et al.'s [1] review showed that most experts were interested in the research topic 'Frugal approach to innovation in SME and Startups'. However, very few reports exist which present specific frugal design or innovation approaches [2]. This gap may be due to the emergent nature of the topic.

Initially, frugal solutions were primarily described using features of the products and services [1]. Only recently were frugal innovations understood as solutions that fulfil specific criteria [3] and a resultant of people-oriented approaches executed within the resource constraints of MCs [1]. Therefore, the next pertinent step is to devise strategic approaches to designing frugal solutions.

Frugal design approaches can be developed for non-marginal scenarios as well. For example, Mourtzis (2018) [4] presents novel uses of high-end ICT technologies (augmented reality) to enable product customisation in an organisational context by combining it with PLM solutions, thus arguably enabling frugal design. However, this thesis is specifically concerned with frugal design approaches and strategies for MC. Based on this, the search and review were narrowed to only assess design approaches and methodologies suitable for MCs.

Although there are relatively fewer *design* approaches, there have been several attempts to define principles and guidelines for a design process in MC [5]–[8]. A summary of key guidelines was most recently presented by Jagtap [5], presenting ten design guidelines for developing ‘integrated solutions’ for ‘marginalised societies’. Jagtap’s work echoes our findings from the literature review (see Appendix A and discussion of previous chapters). Despite the enlightening results, it is difficult for designers to put such guidelines directly into practice due to their abstract nature [2]. Therefore, appropriate design approaches are needed which operationalise such guidelines.

Here some approaches which help design solutions for MC identified through an extensive literature search are critically reviewed

Whitney and Kelkar’s [9] work is among the first to discuss a design approach for MC. Although they do not present a stringent framework for design, they highlight the major stages needed in such a design process. Their process starts with secondary research to understand the problem, followed by ethnographic studies of the context (using a POEMS design tool) and conceptualisation of the solution. They highlight the need for system-level solutions to meet the diverse needs of the context. Reviewing their work from the perspective of requirements presented in chapter 3 shows that many criteria are not met in such an approach. More or less, their process is closer to an NPD process, albeit with significant considerations to meeting social and system-level needs.

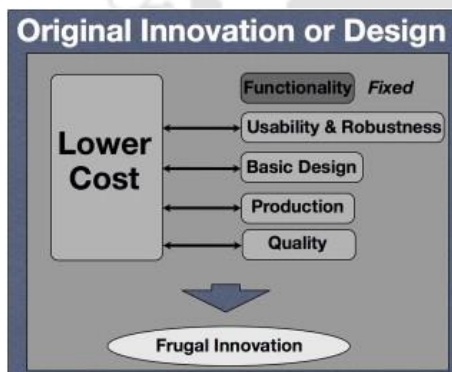


Figure 4.1: Frugal design methodology presented by Rao [10].

In another report, Rao presents a methodology for developing frugal innovations [10] (Figure 4.1). In this methodology, the author uses NPD approaches as a foundation, and the frugal aspects are brought on through an extensive optimisation process. The first step of the suggested methodology is the detailed design of the solution using existing methods. The second step is assessing feasibility for developing a frugal solution, and the final step is optimising the solution based on certain frugality criteria. Besides this, Rao suggests proximity to the context when designing the solution.

There are some similarities between Whitney and Kelkar’s and Rao’s prescribed approaches. In both approaches, the design process is highly similar to the typical NPD process with appended variations. Literature suggests that typical NPD processes are inadequate in tackling the complexities of design for MC [2]. Also, the methodologies do not consider many of the recommendations for design, such as in-depth understanding of the context[5], using co-design methods[11] and considering a broadened design scope [12].

The methodology presented by Castillo et al. [7] is among the most comprehensive. Although the work is not very recent (2012), it presented pertinent design guidelines, strategic approaches and a methodological framework for design for the base of the pyramid contexts. The model emphasises

the iterative nature of design and presents many qualitative and design research tools which can accompany its implementation. Figure 4.2 shows the diagrammatic representation of Castillo et al.'s model.

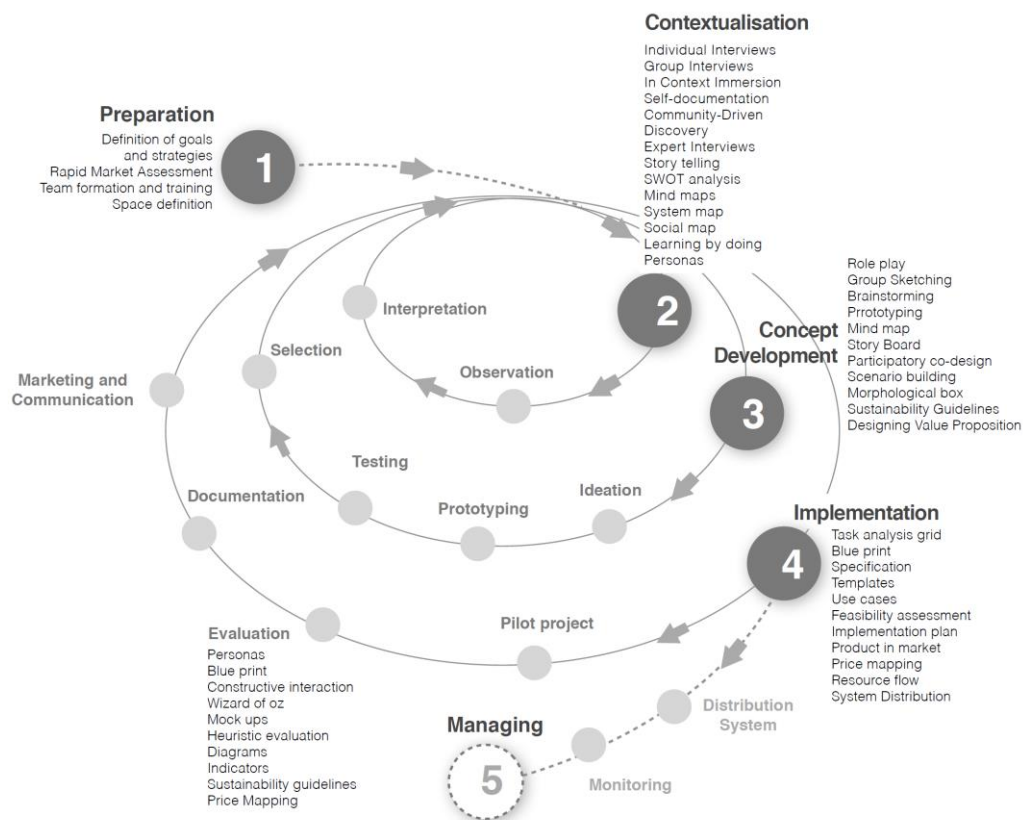


Figure 4.2: A Methodology of Design for Base of Pyramid Proposed by Castillo et al. [7]

Castillo et al.'s [7] proposed methodology consist of four main stages: preparation, contextualisation, concept development, implementation and managing. The preparation stage is for defining the objectives of the design project and project planning. The contextualisation phase is related to design research and opportunity identification. Concept development is related to developing holistic design concepts, and implementation involves developing holistic components such as business and service models. The managing stage is a transition stage where designers monitor and test the solutions through pilots and other evaluation methods.

Although fairly comprehensive, Castillo et al.'s model does not incorporate specific frugal design guidelines. Specifically, the model does not consider product architecture design or other analyses that make the embodiment frugal. It is assumed that designers will consider such aspects independently based on their knowledge of frugal design guidelines. Furthermore, it does not consider how product solutions and system-level strategies interact or affect the design process. Considering the requirements generated in chapter 3, the model does not specify research types or how such co-creative aspects are integrated (although authors emphasise the need for participatory approaches).

Another novel framework, with a special focus on developing appropriate rural technology, is presented by Bhattacharjya and Kakoty [13]. Their product innovation framework is based on

experiences with RuTAG projects that aim to develop technical solutions for problems faced in rural communities. The framework recommends four design stages: need identification, technology search, design and development, field trial and technology transfer. The uniqueness of the methodology is in its flexibility. Authors suggest that sub-stages for each main stage depend on the project and the context. Thus, each main stage is further elaborated into multiple sub-stages with varied goals when planning the project. The model is practical since it considers the organisational structure within which the framework is executed, thus incorporating aspects such as funding assessment and technology roadmap.

However, there are a few shortcomings of the model by Bhattacharjya and Kakoty [13]. Firstly, the model does not consider system-level strategies needed for implementing the solution. The model also does not consider specific service design and dissemination strategies since it concludes with technology transfer. Co-design methodologies and specific methods for developing product architectures are also not considered in the model.

Brem and colleagues have two recent attempts at formulating design frameworks for frugal design [2], [14], which are also the most unique. Brem et al. [2] present a design methodology for developing frugal solutions for MC by combining ergonomic analysis based need-finding process and NPD approach. They call the method the frugal NPD or fNPD approach. The process considers collaboration with end-users for identifying the need and developing design concepts. The process consists of three main phases further subdivided into multiple sub-phases. The figure below shows the proposed process.

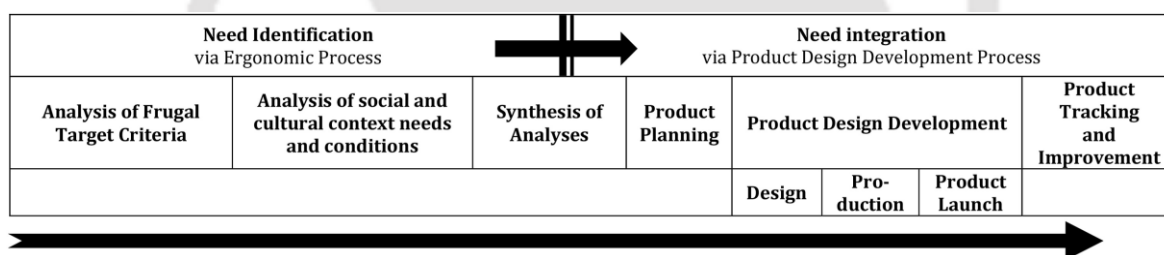


Figure 4.3: Model for the design and development process of frugal products by Brem et al. [2]

The main shortcoming of the model considering established frugal design guidelines is the lack of holistic and strategic considerations in product development. Also, the process considers only a single way of identifying needs for the design. Although ergonomic analysis is a good way to identify needs, it is only suitable in contexts with high physical interactions with the product. For example, if the need calls for a community water filter design, ergonomic analysis can only identify a portion of user needs. The case study presented by Brem et al. (a hand cart for picking waste in the Brazilian context) lends well to the type of design process proposed. However, the process is not generalisable across different product types. In fact, in the subsequent work done by Brem and colleagues [14], they show an entirely different way of identifying design opportunities, further confirming that the model proposed by Brem [2] is not generalisable to all design scenarios.

The second recent methodology is by Agarwal et al. [14]. The proposed model identifies new design opportunities and requirements based on the constraints to the design process. The model is novel in its use of design constraints presented by the problem and the context to create new features of a frugal product. The process focuses on the front end of a design process (i.e. identifying design opportunities) and considers using typical NPD processes for further development. Four stages are prescribed in the model. First is identifying constraints that keep the

status quo; second is a root cause of the constraints; third is developing specific product features mapped to each constraint; and finally, developing a product prototype.

Agarwal et al.'s [14] process illustrate the strength of leveraging constraints in MCs for opportunity identification. Such a design thinking process can be considered a staple of the frugal mindset [15]. However, the proposed approach has some shortcomings as well.

Firstly, the proposed process depends on a typical NPD approach that, as discussed, is not entirely suited to tackle design projects in MC. Second, the methodology does not incorporate key requirements such as considering strategic aspects of design, co-design approaches, and broad scope to the development process. Also, process-wise, it is unclear how the constraints are to be translated to new product features and design opportunities. The authors do not provide any specific tools to do so as well. Nonetheless, the unique perspective presented in the paper can be built upon and will most definitely yield positive results.

Apart from the notable frameworks and approaches discussed above, some more prescriptive design frameworks were also encountered. Unfortunately, these did not meet many key requirements identified and the frugal design guidelines. The models were abstract or concentrated on only a few parts of the design process. Still, these frameworks are acknowledged here for the sake of completeness.

Mattson and Wood[16] provide a generic method and strategy for solution finding when designing for the base of pyramid contexts, attempting to operationalise some design principles they present in the same report. The model is not necessarily a design process but a thinking process. Hence its direct application in practice is limited without significantly building upon it, for which no attempts were uncovered.

An interesting model for understanding and evaluating solutions and their socio-technical interactions with the context is presented by Jagtap and Kandachar [17]. The model is a framework for understanding the effect of design solutions on MC. Although authors suggest its potential as a design approach, it is difficult to implement as a methodology due to its abstractness. The model seems more suited for understanding, cataloguing, and structuring existing solutions for MC.

Finally, some relevant research originating from the Industrial Design Engineering Department at TuDelft, Netherlands, was uncovered [18], [19]. The proponents suggest a framework for design in BoP Contexts. The proposed framework defines the scope of collaboration and co-design needed for such design contexts. However, the framework is abstract, making it difficult to apply in practices directly, and it only considers certain aspects of the process (collaboration and co-creation). Specific research where the model was translated or operationalised into a relevant design methodology was also unavailable.

One of the main criticisms of prescribed approaches is a lack of theory-driven research to verify their effectiveness [17]. Nearly all of the models reviewed were presented as the results of literature reviews or project experiences without taking any steps for empirically validating or implementing them as design supports. Since the prescribed models present novel ideas, it is important to translate them into tools and supports for easier implementation by designers.

Understanding the existing design approaches led to identifying their main strengths and shortcomings. The reviewed approaches also set a benchmark for future work in the field.

Two novel frameworks were synthesised based on the outcomes of prior research. The first framework presents a systematic approach for conceptualising frugal and holistic solutions. The second framework provides a way to understand the marginal context and evaluate design concepts. These frameworks mitigate most shortcomings of existing approaches (to the best of our knowledge) and build upon their strengths.

4.2 Frugal Design Conceptualisation (FDC) Framework

The FDC framework aims to provide a basis for planning and executing a holistic frugal design process. The framework can be used to identify and organise specific design tasks in a structured manner when developing new concepts. This section presents the process in which the FDC framework was developed and discusses it in detail.

4.2.1 Background and Methodology of Synthesis

The research gaps identified in Chapter 1 led to formulating a research objective to develop frameworks for the systematic conceptualisation and evaluation of frugal design concepts. The Frugal Design Conceptualization (FDC) framework was devised to meet this objective.

The retrospective analysis of design projects presented in the previous chapter culminated in a list of requirements for an effective frugal design approach and a solution proposal's conceptualisation. These requirements formed the basis of the FDC and were closely referred to when synthesising the framework. The table below summarises these requirements:

Table 4.1: Summary of requirements for an effective frugal design approach

Group	Requirements for an effective Frugal Design approach
Project Scope and Time Frame	<ul style="list-style-type: none"> • A frugal design approach must have a broadened scope to include design, development and testing of the Solution Proposal • Designers must be able to clearly define the end goal and the outcome in a frugal design approach. The approach should provide a means to define criteria for project success. • Ideally, the outcome of a frugal design approach should be a detailed plan of the deployment, impact assessment, and scaling up of the product design and the solution proposal. • The frugal design approach must accommodate redefining and reinterpreting the initial design brief to broaden the project scope. • One of the first steps of an effective frugal design approach should be planning to accommodate the broadened scope.

Two Research Types	<ul style="list-style-type: none"> • A frugal design approach must have two distinct phases in which design research is conducted. In the first phase, the details of MC must be understood clearly, and in the second phase, the users' daily lives must be studied. • The approach must encourage designers to execute both research phases even when product embodiment complexity is low. • Designers must interview visionaries, stakeholders, and users to adequately understand the context. • Selected visionaries, stakeholders and users should be included throughout the project using participatory activities.
Redefining Project Brief	<ul style="list-style-type: none"> • A frugal design approach must have a stage for redefining the project brief. • The analysis of the two-phase research outcomes must result in a reformulated design brief.
Co-Design and Collaboration	<ul style="list-style-type: none"> • A frugal design approach must accommodate identifying appropriate stakeholders with whom designers can collaborate throughout the project. • A frugal design approach must have at least three distinct co-design activities of Participatory research, Co-Creative idea generation and Co-Evaluation. • Designers must be able to plan the co-design activities and develop appropriate tools to support them.
Strategic Design Considerations	<ul style="list-style-type: none"> • In an effective frugal design approach, strategic design aspects must be considered early in the design process, together with product design ideation. • Value chain configuration, end-of-life planning and income generation opportunities must be explicitly considered in a frugal design approach. • Detailing strategic design aspects must be done along with detailing the product embodiment and architecture design
Testing and Evaluation	<ul style="list-style-type: none"> • An effective frugal design approach must consider testing and evaluating the product concept and solution proposal within the design scope. • The strategic aspects of the design must be evaluated as rigorously as the product is evaluated in performance parameters. • In an effective frugal design approach, measurable success criteria and a plan for impact assessment of the solution must be clearly defined.
Tools, Methods and Frameworks	<ul style="list-style-type: none"> • An effective frugal design approach incorporates specific tools and frameworks for supporting the project's design research and co-design activities. • Existing tools and methods for product design must be compatible with the frugal design approach. • An effective frugal design approach is structured and flexible.

The synthesis of the FDC framework was an interpretative exercise similar in nature to a design process. First, the list of recommendations and guidelines was reviewed and interpreted as design tasks and activities. Similarly, for each project type shown in Table 2.1, the researcher identified specific design tasks needed to meet various design guidelines and recommendations. In many cases, the recommendations could be met only with a series of interconnected design tasks. Several design tasks were also outlined based on the insights gathered from the retrospective analysis study. After outlining these tasks, duplicates were identified and eliminated, and the remaining were prepared for an iterative affinity mapping exercise.

Each of these design tasks was then noted on sticky notes and iteratively clustered and categorised in a series of affinity mapping exercises using the KJ method [20], [21]. The sessions were conducted with student volunteers and the author in a participatory manner. Similar design tasks were first grouped in an attempt to reduce the overall number. After that, the sticky notes were arranged in a sequence that indicated a linear process. The requirements list (Table 4.1) dictated the sequence of tasks and the overall flow. In other cases, tasks were accommodated in the sequence that made the most logical sense to the group. Some tasks were found to be outliers and were kept aside for later review. Some tasks also made the most sense if they were done in parallel. Following this process resulted in a flow of design tasks.

Next, in a similar affinity mapping session, the tasks in the sequence were abstracted and clustered. The objective was to identify broad design phases in the whole sequence. Tasks that seemed related or made the most sense if conducted within a single design phase were clustered together. The requirements list was used to direct the sequencing and clustering exercise. Each cluster was given a name to designate its overall scope or goal. The clustering process was iteratively done till no new clusters could be created without sacrificing ambiguity. This exercise resulted in a sequential process containing nine clusters.

Finally, the affinity mapping results were reviewed in light of the previous research outcomes. For example, one of the requirements states that three types of co-design activities are needed. Other findings from prior research highlighted overarching needs for gaining a deep understanding of the context, generating strategic design ideas, formulating a holistic ‘solution proposal’, and increasing project scope to include solution evaluation. Based on such insights, four design phases were created in which the nine clusters of design tasks were arranged. Each of the nine clusters thus formed the sub-phases of the FDC framework.

4.2.2 Description of FDC Framework

Frugal Design Conceptualisation (FDC) is a framework for planning, executing and creating supports for a ‘systematic conceptualisation of holistic and frugal product design solutions for marginal contexts’. The framework is graphically represented in figure 4.4.

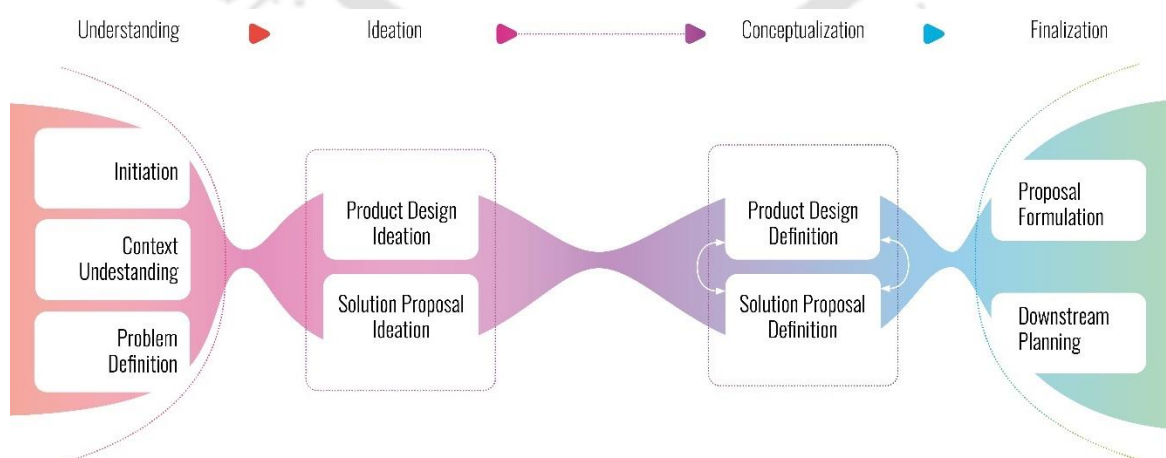


Figure 4.4: The Frugal Design Conceptualization (FDC) framework presents a systematic approach for conceptualising frugal and holistic product design solutions for marginal context.

'Systematic conceptualisation' is an approach for designing concepts in a structured manner. A 'Holistic concept' means that the design incorporates the components of a solution proposal, namely service design, business models, dissemination and impact assessment, in addition to product design and embodiment. 'Frugal solutions' are solutions that are significantly affordable than existing solutions, fulfil certain core needs and are optimised to function reliably. 'Marginal contexts' are social scenarios within a specific geographical boundary where the people have low income, low capabilities, low freedom and lack access to infrastructure and institutional support.

The framework shows four phases that must be executed in sequence for an effective frugal design for MCs. These phases are described below:

- 1 the **Understanding** phase is related to gaining a deep understanding of the context and users lives resulting in a redefined brief. The phase contains three sub-phases of Initiation, Context Understanding, Problem Definition
- 2 The **Ideation** phase is related to generating product design and strategic ideas, resulting in multiple Solution Proposals and product concepts. The phase consists of two sub-phases of Product Design Ideation and Solution Proposal Ideation.
- 3 The third phase is the **Conceptualisation** Phase and concerns iterative detailing of the Product Design and Solution Proposal. The phase consists of two iterative phases of Product Design and Solution Proposal Definition.
- 4 The fourth phase is the **Finalisation** Phase, where implementation, impact assessment and downstream development is planned. This phase consists of two sub-phases of Proposal Formulation and Downstream Planning.

The structure of the FDC framework is suggestive of the milestones and iterations in a design project. Firstly, each phase represents a significant milestone in the frugal concept design exercise. Completing the various sub-phases of the understanding phase, for example, suggest that sufficient research work has been conducted and the team is ready to move into the next phase. Second, the grouping of the sub-phases into a single phase was done to highlight the iterations needed in the project. Most major iterations are likely to happen between the sub-phases rather than across phases.

The phases of the FDC framework were intended to be more abstract and general. It is these sub-phases that make it a suitable approach for frugal design. The sections below discuss each phase and its sub-phases and provide their objectives and goals.

4.2.2.1 Understanding Phase

The overall goal of this phase is for designers to deeply understand the context and its users. In the first sub-phase of the framework (*Initiation*), the designers initiate the project through discussion with project initiators or clients. The preliminary project planning activities, Literature reviews, identifying existing solutions and necessary agreements for the project are done in this stage. The goal of the sub-phase is to create project plans, understand product types and complexity, and identify stakeholders for the participatory execution of the project.

In the *Context Understanding* sub-phase, designers conduct various research activities to understand the context and the users' daily lives. The two types of design research activities are conducted in

this sub-phase. The goal in this subphase is to collect extensive research and interview data and understand the constraints of the MC. Designers also conduct participatory research activities in this sub-phase.

The third sub-phase, *Problem Definition*, is where the research data is analysed to identify key insights, design requirements and design directions for further development. The goal of this sub-phase is to redefine the project brief and identify specific design opportunities. The understanding phase involves selecting a specific design brief for further development and the necessary agreements with the project initiators.

It can be seen in Table 4.1 that the three subphases meet many requirements related to having two types of research, Co-design and collaboration and Redefining Project Brief. The overall outcome of the understanding phase is a deepened understanding, an organised research dataset and new design opportunities. Our literature review and project experiences also suggested that a deep understanding of the context can help build a frugal mindset[15]. Therefore, effective implementation of the three sub-phases could help designers develop a 'frugal mindset' for guiding the design process.

4.2.2.2 Ideation Phase

In this creative phase, designers explore multiple ideas for the product and the solution proposal. Product ideas are generated without a restriction of feasibility or interoperability with the solution proposal. Designers employ various ideation tools, such as brainstorming and 6-3-5 methods. Similarly, preliminary conceptual models of services, business strategy, and dissemination plans are developed using systems design, service design, design thinking, and visualisation tools. The ideation phase aligns with Co-Creative idea generation, the second set of participatory activities needed for an effective frugal design approach. The outcome of the ideation phase is a database of possible ideas for the product concept and solution proposal.

Overall the phase is divided into two sub-phases: *Product Design Ideation and Solution Proposal Ideation*. The phase starts with a review of the selected design brief. The designers carefully delineate the insights and requirements related to the product concept and solution proposal. With this, new product ideas are generated using available methods and tools in the first sub-phase. The goal of the first sub-phase is to identify as many product design ideas and working principles that fulfil the design briefs.

The *Solution Proposal Ideation* sub-phase is unique to the frugal design approach. Here, designers focus on generating novel ideas for services, strategies, distribution, advertising and impact assessment of the solution proposal. This goal here is to generate strategic ideas without considering interoperability and compatibility with the product design ideas. Designers can use tools, methods and approaches from service design, systems design and business model design to generate as many ideas as possible.

Finally, the phase ends with a preliminary evaluation of the outcomes and selection of a set of promising product design and solution proposal ideas. The overall outcome of the ideation phase is an exhaustive database of preliminary ideas for the product design and solution proposal.

4.2.2.3 Conceptualisation Phase

The Conceptualisation phase is an iterative stage where designers select and develop ideas and improve the interoperability of the product concept and the solution proposal. The goal of this phase is to develop the product architecture, detail the solution proposal, and test the outcomes. The phase also encompasses the participatory evaluation of the overall design solution. The selected ideas are combined, and the interoperability of the product concept and solution proposal is ironed out.

Concept selection exercises are also done using various engineering design and system design tools. Designers prototype and test the product concepts and solution proposal using established tools and methods. Various reliability engineering methods such as DFMEA, DFM, and systems design methods such as stakeholder maps, service walkthroughs are also designed.

The goal of the first sub-phase, *Product Design Definition*, is to create a detailed product concept. Here, the architecture of the product, its embodiment and construction are clarified. However, prior research insights say that the solution's strategic aspects may considerably affect the product architecture. Due to this, several design iterations may be needed using physical and digital prototyping methods.

The goal of the *Solution Proposal Definition* sub-phase is to detail the solution proposal. Designers develop necessary artefacts, stakeholder maps and service journey maps to detail such aspects. Evaluating the overall solution using participatory methods is also part of this sub-phase. Necessary tools, artefacts, prototypes needed for the participatory appraisal are also developed.

The conceptualisation phase ends with an evaluation and detailed documentation necessary for implementing and further developing the holistic solution. Overall there are two outcomes of this phase. First, detailed product concepts, prototypes, CADs, and the product concept evaluation in technical and qualitative parameters. Second, a comprehensive solution proposal, including the system design for the key lifecycle stages, service plan, dissemination plan, branding and marketing activities.

4.2.2.4 Finalisation Phase

In the Finalisation phase, the designer develops strategies for implementation, impact assessment and downstream development of the holistic solution. Designers also prepare documentation of the work done and present the final product concept and solution proposal to the stakeholders. The design team, project stakeholders and the initiators collaboratively decide on the solution's deployment. Any agreements or signoffs on the concept design can be done as part of the phase.

The two sub-phases for this phase are *Proposal Formulation* and *Downstream Planning*. The goal of the first sub-phase is to develop a detailed account of the design work and the final solution necessary for further development. Typically, the outcomes of the sub-phase are comprehensive reports and control documentation. In the second sub-phase, the goal is to collaboratively plan the deployment and impact assessment of the solution. The designer also develops metrics for evaluating the success of the Solution Proposal. The overall outcomes of the 'finalisation' phase take the form of reports, prototypes, budgets, finalised drawings and agreements.

In summary, Table 4.2 shows the main objectives, inputs and expected outcomes for each sub-phase of the FDC framework.

Table 4.2: Objectives and expected outputs of each subphase in the FDC framework.

Sub-Phase	Objectives	Inputs to sub-phase	Expected outputs
Initiation: in this sub-phase initial project work is conducted.	<ul style="list-style-type: none"> Form design team. Clarify the initial design brief. Gain a preliminary context understanding. Evaluate project complexity. Plan project timeline and scope. 	<ul style="list-style-type: none"> Client Brief Assessment of team motivations. 	<ul style="list-style-type: none"> Design team formulation. Project timeline and milestones. Project complexity evaluation. Preliminary research and understanding of the brief.
Context Understanding: This sub-phase is for a deep understanding of the context and users.	<ul style="list-style-type: none"> Find relevant literature and existing solutions. Identify stakeholders and visionaries. Conduct Participatory Research activities. Understand stakeholder motivations, users daily lives and contextual constraints. 	<ul style="list-style-type: none"> Preliminary research data and context details. Plan for Participatory Research and other design research activities. 	<ul style="list-style-type: none"> List of benchmark solutions. Stakeholders for participatory design. Outcomes of Participatory Research Activities. Design research data Understanding of users lives and the context.
Problem Definition: The sub-phase where the project brief is redefined.	<ul style="list-style-type: none"> Analyse research data to create insights and requirements. Identify Initial strategies to mitigate contextual constraints. Develop Measurable project success criteria. Define the design directions and opportunities. Redefine Design brief. Develop Research Reports. 	<ul style="list-style-type: none"> Design research data. Understanding of contextual constraints and users lives. 	<ul style="list-style-type: none"> Novel Design insights, opportunities, strategies and requirements. Project impact scope and measurable success criteria. Redefined design brief. Research reports
Product Design Ideation: new product ideas are generated in this sub-phase	<ul style="list-style-type: none"> Analyse benchmark products Define product functions and technical specifications. Conduct participatory ideation sessions. Plan for prototype testing. Organise and select promising Ideas. 	<ul style="list-style-type: none"> Benchmark Solutions. Design Insights and requirements. 	<ul style="list-style-type: none"> Product's core functions, features and technical specifications. Novel Ideas for Product Design Selected list of Ideas. Plan for testing product prototypes.

<p>Solution Proposal Ideation: In this sub-phase Strategic Ideas are developed, and a solution is selected for development</p>	<p>Analyse strategic aspects of benchmark solutions. Develop strategic design requirements. Conduct participatory ideation for strategic Ideas. Evaluate and select a holistic concept for development.</p>	<p>Benchmark Solutions. Design insights and strategies for mitigating constraints. Measurable success criteria.</p>	<p>Ideas and opportunities for novel Solution proposal concept. List of strategic design ideas for solution proposal and Product Life Cycle. Selected Product design and solution proposal for further development.</p>
<p>Product Design Definition: Sub-phase where the product is detailed, embodied and tested</p>	<p>Develop architectures, schematics and geometric layout for the product concept. Develop mockups and prototypes. Evaluate the product design</p>	<p>Selected Product Idea. Technical specifications and core functions. Design insights, requirements and opportunities. Results of preliminary product evaluation and testing. Details of Solution Proposal and its effect on the product.</p>	<p>Frugal Product Architecture and embodiment. Product Prototypes and Mockups. Results of Prototype and design evaluation.</p>
<p>Solution Proposal Definition: Sub-Phase where the final solution is evaluated and selected.</p>	<p>Conceptualise the detailed models for business, services and dissemination of the solution. Conceptualise payment models and income generation opportunities. Conduct participatory evaluation of solution proposal and product design.</p>	<p>Selected Product and Strategic Ideas. Results of the preliminary evaluation of strategic ideas. Design insights, requirements and opportunities. Measurable success criteria</p>	<p>Service and System design blueprints. Plan for dissemination, distribution, marketing and training. Costs, pricing and financial projections. Value chain configuration and stakeholder benefits. Results of participatory evaluation of the holistic solution.</p>
<p>Proposal Formulation: Sub-phase for reporting and documentation</p>	<p>Develop communication materials. Develop technical documentation.</p>	<p>Details of final Solution Proposal and Product Concept. Results of Product testing. Results of Participatory Evaluation.</p>	<p>Reports and Documentation of Project. Control drawings, Prototypes and engineering studies. Visualisation and communication materials</p>

Downstream Planning: Sub-phase for downstream development and impact assessment planning	Plan the initial deployment, pilot testing and impact assessment. Initiate collaborations for scaling and deployment Identify additional funding and support opportunities.	Redefined Design Brief. Design Insights and requirements. Measurable success criteria. Research reports and technical documentation.	Pilot manufacturing and Scaling plan. Proposal for Impact assessment Agreements, Signoffs and intellectual protections.
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4.2.3 Implementing FDC framework

Effective implementation and operationalisation of the FDC framework can be done by developing ‘Design Activities’ for each sub-phase. Design Activities are specific outcome-oriented tasks, completing which fulfil the objectives of sub-phases and add to fulfilling each phase’s overall goals and objectives.

Creating the ‘Design Activities’ is an interpretative exercise and depends on the project complexity, resources and timeline. Design activities can be created at various levels of abstraction. For example, a version of FDC implementation may have only a few Design Activities at a high abstraction level, effectively combining multiple tasks into a single Activity that meets the objective of one or more sub-phases. In contrast, another implementation may have several Design Activities providing a more granular level of thinking and control over the project.

An example of a highly abstract Design Activity will be ‘*Designers conduct interviews with the Stakeholders*’. Alternatively, the same objectives could be met by several Design Activities together presented at a lower abstraction level, such as ‘*Plan the Interviews with Stakeholders*’, ‘*Create Questionnaires for Interviews*’, ‘*Conduct Interviews*’ and ‘*Analyse the results of the Interviews*’. Therefore, different activities could be derived based on the project and the MC being served. Design activities are adapted from classical NPD, Systems design, Service Design, Business modelling approaches, and frugal design guidelines (see **Appendix A**).

Project complexity may also significantly affect how FDC is operationalised and which Design Activities are chosen for implementation. Lower complexity projects may not need as many Design Activities or could support multiple activities conducted simultaneously. Similarly, high complexity projects may need to consider additional Design Activities or execute a single Design Activity in multiple ways. Alternatively, time and resources available in the project also dictate the chosen Design Activities. Chapter 2 outlined a way of assessing project complexities in frugal design projects.

The FDC framework was specifically developed for product design-oriented projects. Hence, its appropriateness for other projects, such as the design of interactive systems, computer applications, is unclear. However, the framework could be easily adapted and modified to suit such applications. Frameworks inapplicability in other project types is due to its emphasis on Product design and embodiment in some sub-phases of the framework.

It can be argued that the FDC framework enables a frugal mindset by deep contextual research and understanding users’ lives. However, a solution’s frugality is highly dependent on the Design Activities, tools, and methods considered during its implementation.

Table 4.3 below presents an example set of Design Activities for each Sub-Phase to illustrate how the FDC framework could be implemented. A list of tools that can help designers during each sub-phase is also shown. Based on the discussion above, the FDC framework is flexible and can accommodate different implementations depending on project type, complexity, time, and control needed in project planning.

Table 4.3: An Example Implementation of the FDC framework through Design Activities and relevant tools.

Sub-Phase	Examples Design Activities	Example of Design Tools
Initiation	Clarification of Project brief. Initial field visits and interviews with project initiators. Team building exercises	Project Planning tools Gantt and Milestone Charts
Context Understanding	Literature Review. Identification of Existing solutions. Development of artefacts for conducting participatory exercises. Interviewing stakeholders and visionaries in the context. Field visits and observational studies	Design Research Methods, Ethnography tools, Semi Structured Interviews, Focus Group, User Narration, Context Mapping, Cultural Probes, Persona, Storyboards
Problem Definition	Analysis of recorded interview data. Writing research reports. Getting approvals of redefined brief	Theory of Change, Role Playing, Mind Mapping, Brainstorming, Image Boards,
Product Design Ideation	Analysis of existing solutions and benchmark products. Participatory Ideation with Users. Developing Initial Prototypes and Mockups.	Paper Prototyping, Mockups, Experience Prototyping, Appearance Models, Body Storming
Solution Proposal Ideation	Value Chain Analysis of existing solutions. Develop Service and System design Ideas. Develop the business model and dissemination Ideas. Select promising Strategic Ideas	Market and Retail Research, Touchpoint Analysis, Perceptual Mapping, Trend Analysis, Ansoff's Matrix, Stakeholder configuration maps, Business model canvas
Product Design Definition	Develop CAD and digital models for engineering analysis. Create Testing prototypes. Reliability Analysis of Product.	Function Structure Modelling, DFMEA, DFM, Morphological Charts, Design by Analogy, SCAMPER, Syntectics, Frugal design guidelines, CAD modelling, Fault Tree Analysis
Solution Proposal Definition	Develop service and systems design configuration and related artefacts. Develop Income generation opportunities. Conduct participatory evaluation of the holistic solution.	Stakeholder configuration maps, Business model canvas, Service Design tools, Break Even Analysis, Cost-benefit analysis, Eco-Design Checklists, Decision Matrix

Proposal Formulation	Develop technical drawings for manufacturing. Create project visualisations and marketing materials.	CAD modelling software, Rendering and visualisation, Posters and Pamphlets, Mock Advertisements
Downstream Planning	Create a plan for pilot testing. Initiate work for pilot manufacturing and pilot testing. Create Measurable criteria for assessing long term success.	Quick LCA, Experience Prototypes, Journey Maps

Although the construct of Design Activities provides flexibility to the operationalisation of the framework, it may be a hindrance if designers are asked to create a new set of Activities every time in a project. Therefore, there is an opportunity to develop a tool that practically helps implement the FDC framework. The tool could be a comprehensive pre-defined set of Design Activities developed considering a generic medium complexity project. Designers can then select relevant Activities from the set and implement them appropriately based on their project's complexity and available resources.

The FDC framework was developed specifically for enabling holistic frugal design in MC. However, the framework's layout and its sub-phases may give an impression of generalizability. i.e. the framework may seem applicable for all project types, not just for MC. Therefore, it is important to clarify how the FDC is suitable for design in MC contexts only.

4.2.3.1 Suitability of FDC framework for design in MC

Firstly, the development of the framework was iterative and derived from specific requirements and design guidelines for an effective frugal design approach. Due to this, the scope considered in the FDC framework is much larger than in typical NPD processes. Following the FDC in a general NPD project not related to the MC may be cost or time prohibitive. In a frugal design project for MC, additional project time is justified due to the ambiguity in the context and the increased scope needed. Therefore, designers can justify implementing the FDC framework in the MC but not in affluent contexts where NPD is employed.

Secondly, in typical NPD projects, it may not be necessary to understand the context, infrastructure, and constraint in depth. Such depth is not required because NPD processes are typically executed within organisations where the downstream supply and product execution are clearer. For example, the company may have existing suppliers, vendors, distributors and retailers. Even if that is not the case, existing supply chain networks provide a template for solution deployment. Research insights indicate that such structured supply chains do not exist in MC. Designers thus need to understand the context and device value chains in more detail to support new solutions. The FDC framework incorporates such in-depth context understanding and system-level development needed in its sub-phase goals. Hence it is more suitable for supporting the design process in MC instead of in affluent contexts.

Finally, the construct of 'Solution Proposal' is ingrained into the FDC framework. The outcome of the framework is a concept that combines the product design solution and the solution proposal. In typical NPD processes for affluent contexts, designers do not have control over such pervasive aspects of the solution. In such scenarios, several aspects of the solution proposal are decided by an

organisation’s marketing or executive branches. This characteristic makes the FDC framework unsuitable for projects where the design team cannot make holistic decisions.

Moreover, Due to the ambiguity in the context or the unstructured organisational networks, the project initiators benefit and, in most cases, seek such holistic decisions from designers working on projects for MC. This characteristic makes FDC most suitable for design projects in MC.

4.3 Context Evaluation Hierarchy (CEH)

Constraints in the MC play a crucial role in shaping the success of design solutions. Constraints are ways in which designers are inhibited in executing any design process as intended in an MC. A deep understanding of the constraints becomes necessary for uncovering the design requirements in the initial phase of the FDC framework. During this time, the designer must translate the effects of the constraints into relevant design insights and requirements lists. Another phase where understanding the constraints is critical is when the designer selects promising ideas and evaluates the concept.

The context evaluation hierarchy (CEH) framework presents the various constraints that affect the frugal design process and outlines a practical and objective way for conducting concept evaluation.

4.3.1 Background and Methodology of Synthesis

The extant literature review found two types of constraints: the first type is generally seen in all MCs, and the other is specific to the designed solution. Chapter 1 outlined the general constraints faced when designing for MC as **1) Low income and affordability of people, 2) Low literacy of the people, 3) Lack of access to financial systems, 4) Lack of Support and development infrastructure, 5) Constraints in the market and 6) Weak Governance.**

The extant literature review identified specific design, development, and implementation constraints. Table 4.3 provides a summary of these specific constraints.

Table 4.4: A Summary of the specific constraints for product design and development in MC.

Constraints to product development in MC	Constraints to product implementation in MC
<ul style="list-style-type: none"> • Developing a solution that requires access to electricity and fuel may be difficult due to the lack of appropriate infrastructure [22] • There may be limited or reduced storage capacity due to the harsh climatic conditions and lack of infrastructure.[23] • The capacity to manufacture, distribute and commercialise a device may not be available reasonably close to the context [7] • There may be a lack of access to quality material, manufacturing methods for use in the design [24] 	<ul style="list-style-type: none"> • People are part of social networks that may hinder disseminating services (but these networks may also be leveraged). There may be Resistance to cultural change. Religious and cultural beliefs may hinder the intended method of usage. [24], [26]–[28] • Innovations may change the existing social relationships, which may hinder the use of the solution [29] • Literacy and access to education may stop the effective use of the product [24], [30]

<ul style="list-style-type: none"> • Spare parts, consumables, repair tools, and technical know-how required to make, produce and use the designs may not be available within a reasonable distance from the context. [7], [16] • The target user group may not be able to afford the solution directly.[16] • There may be a lack of trained personal for use and maintenance [25] • Lack of skilled labour for prototyping or manufacturing [26] 	<ul style="list-style-type: none"> • A solution may be used for unintended purposes leaving the status quo for which it was designed intact. [108] • The organisation might face a dearth of subsidiaries or partners that use Sustainable production practices [18], [31] • The government, leaders, heads of communities and peers may influence the distribution and dissemination of the solution. [32] • The people may not choose to spend on the solution despite it being affordable since it does not have a short term or immediately visible benefit [33]
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The retrospective analysis of design projects presented in the previous chapter highlighted that all constraints for the frugal design process could be grouped into four overall categories: 1) **Environmental and Social Constraints**, 2) **Socio-Political and Legal Constraints**, 3) **Production and Infrastructure Constraints** and 4) **Individual Level Constraints**.

The constraints and design guidelines identified from prior research formed the basis of the synthesis of CEH. The methodology of synthesis was similar to that of the FDC framework.

First, the design team reviewed prior research and noted an exhaustive list of factors that affected the design process by interpreting the various constraints and design guidelines. Then, through a process of iterative affinity mapping [20], [21] and axial coding [34] of the extracted factors. The exercise was conducted in a participatory manner with students and researchers. The extracted factors were written on movable cards and clustered into relevant groups in several iterative and participatory sessions. At the end of each session, the researchers defined each factor and cluster as accurately as possible. Then, the four groups of constraints were used to create overall groupings and arrange the various items in a meaningful layout. After, several iterations saturation was reached where the group was satisfied with the layout of the items. This outcome was then reviewed to check its alignment with findings from prior research. The outcome of the exercise resulted in the CEH framework.

4.3.2 Description of CEH Framework

Context Evaluation Hierarchy is a framework for understanding specific constraints that affect the frugal design process in MC and its outcomes. The framework can direct design research and concept selection activities in frugal design projects. It consists of 14 'Parameters' distributed into four related groups. Each of these parameters represents a typical dimension of constraints faced when designing and implementing holistic solutions for MC. Figure 4.5 shows a diagrammatic representation of the CEH framework.

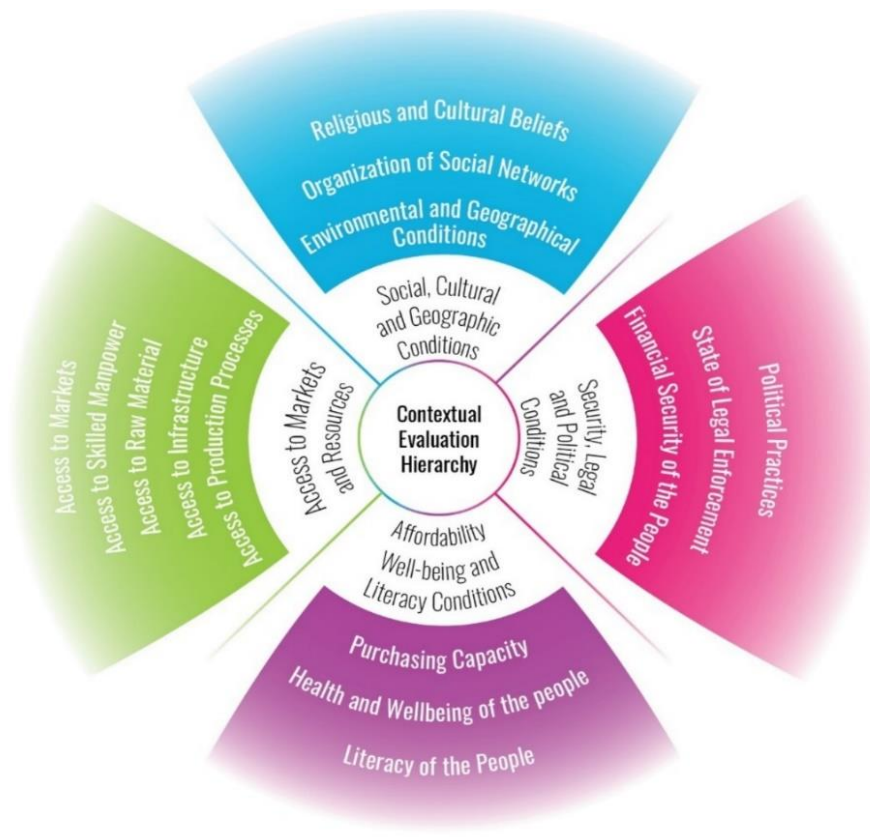


Figure 4.5: The Context Evaluation Hierarchy showing 14 Parameter that affects the frugal design process in MC.

1 'Social, Cultural and Geographic Conditions' of the context.

This group of parameters is related to the natural conditions that arise from the context's environmental, geographical, social, cultural, and religious aspects. Constraints related to such parameters depend on the specific location and population. Even when designers consider the same income group and demographic as their target, solutions may need significant changes due to these parameters. The individual parameters in the group are defined in Table 4.4.

Table 4.5: Description of the CEH parameters in the group: Social, Cultural and Environmental Conditions.

Parameters	Description	Keywords related to the parameter
Environmental and Geographical Conditions	It is the state and variation of weather, temperature, humidity and other natural elements in the context.	Accessibility of the location; Terrain; Weather; Climate; Temperature; Humidity; Location; Terrain; Space; Remoteness; Distance; Travel Time;
The organisation of Social Networks	It is the way people have organized themselves by being part of a community or social group	Community; Cultural Heritage; Social Group; Social Class; Occupational Class; Neighbourhood; Relationships; Followers;

Religious and Cultural Beliefs	It is the trust, faith, or confidence that the people in the context have, on the teachings derived from religion or culture and the social behaviours, habits or rituals arising out of such faith.	Religion; Faith; Culture; Social behaviour; Communal Habits, Rituals; Taboo; Superstition; Division; Segregation; Reluctance to change;
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2 'Security, Legal and Political Conditions' of the context.

These parameters are dependent on the regulations and structures installed by governments and external agencies. The parameters in this group highlight the constraints arising out of vulnerability and inequality faced by people. Constraints along these parameters may significantly affect the participation of users and agencies in the solution's value chain. These may also affect the distribution and scaling of the solution into multiple locations. The individual parameters in the group are defined in Table 4.5 below.

Table 4.6: Description of the CEH parameters in the group: Security, Legal and Political Conditions.

Parameters	Description	Keywords related to the parameter
Financial Security of the People	The people's ability to avail services such as credit, loans and insurance from financial institutions.	Savings; Loan; Subsidy; Insurance; Banking; Micro Finance; Government Schemes; Self Help Group; Taxes;
State of Legal Enforcement	The state of law and order which people face in the scenario.	Law and order; Security; Freedom; Intellectual Property; Legal help; Police Protection; Corruption; Hooliganism;
Political Practices	The influence and effect of political ideologies on the people, including the influence of politicians and community leaders.	Ideologies; Leadership; Lobbying; Bureaucracy; Government Support; Civil rights; Public Information; Hierarchy;

3 'Access to Markets and Resources' in the context

The parameters in this group represent the constraints arising due to a lack of supporting infrastructure, resources and markets in the context. Such constraints typically depend on the geography's overall economic policies and market dynamics. Hence these are rarely fully controlled by the people or the governments. Constraints related to these parameters highly affect a solution's design, development, and manufacturing. The individual parameters in the group are defined in Table 4.6 below.

Table 4.7: Description of the CEH parameters in the group: Access to Markets and Resources

Parameters	Description	Keywords related to the parameter
Access to Production Processes	The ability of the solution provider to find and utilise the required development, production and manufacturing processes in the scenario	Production processes; Manufacturing methods; Machines; Suppliers; Vendors; Dies; Tools;

Access to Infrastructure	The ability of solution providers to use the infrastructure in the scenario.	Reliable Electricity; Fuel; Shelter; Space; Water; Heating; Cooling; Warehouse; Storage; Refrigeration; Internet Connectivity;
Access to Raw Material	The ability of the solution provider to find, utilise and source raw materials for manufacturing and production of the solution.	Sourcing; Transportation; Availability of Materials; Suppliers; Standard Components; Distribution;
Access to Skilled Manpower	The ability to find, recruit and involve a skilled workforce within a reasonable vicinity of the scenario with fair practices.	Recruitment; Skill; Work Experience; Fair Wages; Literacy of Workforce; Professional Education; Travel distances;
Access to Markets	The ability of the solution provider to engage with the market and provide needed solutions to the intended users through fair practice.	Distance to markets; Advertisement; Supply chain; Distribution; Retail and Wholesale; Purchase Processes;

4 'Affordability, Well-being and Literacy Conditions' of the context

This parameter group represents the constraints that arise due to the lack of capabilities [36] individuals face in the context. These constraints directly affect the ability of a person to use the solution. Hence, they focus on generating meaningful needs, insights and opportunities. These constraints also dictate the type of solutions, their costs, and how they will be used. The individual parameters in the group are defined in Table 4.7 below.

Table 4.8: Description of the CEH parameters in the group: Affordability, Well-being and Literacy Conditions.

Parameters	Description	Keywords related to the parameter
Purchasing Capability	The ability of the people in the context to buy and own a solution.	Income; Cost of Purchase; Disposable Income; Running Costs; Maintenance; Disposal; Energy cost; Value;
Health and Wellbeing of the people	The people's physical and mental health condition in the scenario, vulnerability to preventable diseases, and access to healthcare.	Risk; Occupational Hazard; Safety; Exposure; Physical and Mental Health; Work hours; Addiction; Fulfilment; Satisfaction;
Literacy of the People	The level of Literacy, Access to Education, Educational Qualification, Numeracy Skills, Reading and Writing Skills of individuals.	Education; Numeracy Skill; Communication; IT skills; Access to Knowledge; Internet Use;

The CEH framework was developed to support the FDC framework and make it a more suitable approach for frugal design in MC. The CEH parameters are unique to MC and are the driving factors for design in MC. Thus, incorporating CEH in the FDC framework makes it uniquely suited to tackle the design challenges in MC.

CEH can also be considered a template that can guide some of the phases in the FDC framework. Firstly, the 'Context Understanding' sub-phase of the FDC framework is related to gaining a deep understanding of the context and user's daily lives. The CEH framework can be used for directing

the research in this sub-phase. Next, during the solution proposal ideation and definition sub-phases, the CEH framework lends well to evaluating the holistic solutions and selecting appropriate ones for further development. The section below discusses the implementation of CEH in further detail.

4.3.3 Implementing CEH framework

One way of directly implementing the CEH framework is by developing checklists, plans and research questions for or guiding design research activities in the early phases of frugal design. Depending on the type of solution being designed, the complexity and scope, designers can select a set of research questions pertinent to the project and focus their research efforts on them.

Table 4.8 below shows how the CEH framework can be implemented for directing research activities. The table only shows the research questions and activities for the parameters in the group ‘Social, Cultural and Environmental Conditions’. A complete version of the table is presented in **Appendix B**.

Table 4.9: Using the CEH parameters to direct the project’s design research goals and activities. (See Appendix B for complete table).

CEH Parameters	Design Research Questions to answer	Design Research Activities to conduct
Environmental and Geographical Conditions	How will terrain, climate and environment affect the possible solution? Will the context’s location affect the deployment of design solutions?	Field visits to prominent locations in the context. Analysis of transportation of goods in the context. Interviews with stakeholders
The organisation of Social Networks	Which are the prominent social group with whom the solution providers can collaborate? Will the solution affect the social dynamics in the context? Will it be a positive or negative impact?	Interview with visionaries and agencies in the context. Focus group interviews with prominent people in the context.
Religious and Cultural Beliefs	Will the cultural and religious practices be compatible with the envisioned solution? Which social practices are hard to change? How does the envisioned solution affect these?	Demographic information. Observational Studies of existing cultural, religious practices and rituals. Observational Studies of users. Interviews and Focus groups

As shown in Table 4.8, various research goals and questions can be formulated based on the CEH parameters. Not all formulated questions need to be deeply answered in a design project. Designers can assess the project requirements and focus their efforts on answering the research questions that impact the project work and solution. Therefore, CEH parameters can help designers take a more directed research work.

Another intent of the CEH framework is for evaluating design concepts at the early phases of the process.

In MC, designers may have a limited understanding of the context. Thus, it becomes difficult to select appropriate design concepts at the early phases of the process. This difficulty may further increase with a broadened project scope [12]. Furthermore, for holistic frugal solutions, the criteria for success are much broader than the performance characteristics in conventional technical systems [17]. Such performance criteria are unclear in early design phases since design requirements are evolving [35]. Hence, a novel method of estimating the effectiveness of concepts in early design phases is necessary. Such a method can ensure that designers shortlist holistic concepts at early design phases and direct their development efforts more appropriately.

The CEH framework can be adapted as the basis of such an evaluation. Solutions can be evaluated based on the degree to which it mitigates, leverages or works within each CEH parameter.

For a more objective evaluation of design concepts, CEH parameters can be used along with structured concept evaluation methods such as Pugh matrix [36, p. 150] or Multi-Criteria-Decision-Making (MCDM) methods [37]. The structure of the CEH framework lends well to the MCDM methods. When using such methods, each parameter is can be given a weight based on its potential effect on the solution. Each design concept can then be evaluated based on how well it mitigates the constraints related to each CEH parameter.

It should be noted that such evaluations using CEH parameters does not supersede concept evaluation using robust technical parameters. Hence the method is mostly suitable for concept evaluation in early design phases. Also, since the parameters are subjective, appropriate modifications of the objective evaluation methods are needed. Literature suggests that hybrid MCDM methods that use fuzzy and rough numbers can help evaluate concepts using subjective criteria such as the CEH parameters [35], [38].

4.4 Discussion

Systematic literature review shows that the research community is interested in understanding how frugal solutions can be designed [1]. However, a limited number of such design approaches were found. The chronological development of existing approaches indicated that they matured with the evolution of frugal design guidelines. Where initial approaches only concentrated on a few design stages [9], more recent approaches prescribe frugal design as a holistic and integrated exercise [39].

However, several shortcomings of these approaches were identified. The overarching shortcoming was that they did not consider co-design activities, holistic aspects, product embodiment, and a broadened design scope within a single design framework. Moreover, most approaches do not explicitly convey how they are practically implemented and operationalised. Considering the novelty and metempirical nature of the approaches to general design practice, it becomes necessary for researchers to develop practical ways to implement such approaches. Developing design supports and tools is a promising way for such practical implementation.

Also, comparing the myriad frugal design guidelines and the approaches that claim to incorporate them, it was seen that significant information was lost to abstraction. Many guidelines get

subsumed into presentations of these proposed frameworks and approaches. A design tool presents the opportunity to include these design guidelines comprehensively.

However, the noticeable shortcoming of existing approaches was the lack of empirical validation. Most were validated through single-case-study design and lacked adequate triangulation [2], [9]. A way to ensure robust empirical validation is by operationalising the frameworks into toolkits and conducting design workshops and exercises [40], [41]. Similarly, concept generation exercises are also common methods for empirical validation and lend well to statistical enquiry and quantitative assessment [42], [43].

4.4.1 Evaluating the Frameworks

The broad research question this thesis set out to answer was, “How can designers design effective solutions for the MC using a systematic approach?”. The FDC and CEH frameworks establish a systematic approach and a method for understanding the effectiveness of designed solutions. However, one of the key shortcomings of existing approaches was a lack of validation and empirical evaluation [17]. Therefore, it is important to establish a means of evaluating the proposed approaches.

In research into design, the validation of theories is typically done through workshops and design exercises [40], [41]. Since most theories and tools are created to support design practice [44], workshops and design exercises provide the closest proxy to live design projects. Therefore, design exercises and workshops provide reasonable insights into the practical implementation and effectiveness of a newly designed tool or theory.

Workshops are empirical studies where a set of subjects are guided in implementing the new theory, and relevant qualitative and quantitative data is extracted from the experience of participants [45]. In contrast, design conceptualisation exercises follow a methodology where participants are given a design exercise that integrates the tools or learnings from some novel theories [43]. In design conceptualisation exercises, the outcomes produced by the subjects are scrutinised, whereas, in workshops, it is the experience of participants. Thus, workshops typically are associated with rigorous qualitative assessments and design conceptualisation exercises with quantitative evaluations.

Although conducting multiple evaluations undoubtedly strengthens the validity of theories, it is an endeavour that was out of scope for our research project due to time and resource constraints. Therefore, a decision was made to evaluate the framework’s effectiveness using a design conceptualisation exercise only, and a workshop-based evaluation has been kept as future work of this thesis.

Based on these arguments, the following research hypothesis was formulated to understand the effectiveness of the FDC framework using a design conceptualisation exercise:

Concepts designed using the FDC framework are perceived to be better than concepts designed using a general design approach by experts when evaluating using subjective parameters

To develop design concepts using the FDC framework, designers have to systematically execute a set of Design Activities that meet the objectives of the various phases of the framework. The concepts generated using the framework represent the results for scrutiny in a design conceptualisation exercise. These results must be better than the results from a general design approach to illustrate the effectiveness of the FDC framework.

Since the concepts generated in such an exercise may not have an associated functional prototype, assessing them on objective and technical parameters would be difficult. However, it is possible to evaluate the concepts based on the experience of experts. The framework can be considered effective if experts perceive that the results from the FDC framework are better.

Moreover, since concept evaluation on technical parameters may not be possible, the CEH framework can be used as the subjective parameters for evaluation. There are some other known ways to subjectively evaluate design concepts [46], [47]. The results can also be compared to check if CEH parameters provide an effective means of subjective evaluation.

The structured evaluation methodology discussed above can help us understand the effectiveness of the FDC and CEH frameworks. This effectiveness is defined based on the ability of a designer to design better concepts using the frameworks. The next chapter presents the experimental evaluation of these frameworks using a design conceptualisation exercise.

4.5 Conclusion

The chapter critically reviewed many existing approaches, frameworks and methodologies for design in MC. However, there are some limitations to the review conducted. Our search was concentrated on design approaches that were directly related to product design for MC. In doing so, some prescribed approaches related to other domains may have been missed. Similarly, some tools in other domains of literature that could be used to support frugal design but were not uncovered in our search.

The chapter also detailed two frameworks, their synthesis methodology and how their implementation is envisioned. Synthesis of frameworks from research insights is inherently an interpretative exercise that depends on the researcher's worldview. A collaborative affinity mapping was followed for synthesising the FDC and CEH framework to reduce such biases. However, due to the qualitative nature of the approach, such biases cannot be entirely avoided.

A notable aspect of the FDC framework is that its practical implementation depends on developing appropriate Design Activities that meet the objectives in the framework. Although this exercise provides flexibility to the framework's implementation, it also adds a layer of subjectivity. Therefore, a design tool to support the implementation of the FDC framework is necessary to reduce such concerns. Consequently, it is imperative to adequately test the framework through empirical validations. The chapter's discussion presented an approach for such an evaluation.

A limitation of the FDC framework is that it is developed to support only the concept design of frugal solutions. The framework ends with the planning for the pilot test and evaluation of the solution. Although design guidelines suggest that pilot tests are an important part of a frugal development [12], considering it within the framework's structure was not meaningful.

Pilot testing is a major milestone in a project that deserves a separate approach. The overall frugal product development lifecycle can be considered as 1) Concept development through FDC framework, 2) Pilot testing and deployment, 3) Scaling up and long-term impact assessment.

There may be a possibility for the development project to branch off into other areas after extensive concept development. Therefore, it did not make sense to define a single approach that covers the entirety of the frugal development lifecycle. Moreover, predicting the requirements for pilot testing, deployment, and long-term assessment is difficult since it depends on the context, problem and project outcomes. Therefore, the pilot testing and deployment phase were not considered within the FDC framework and must be executed separately after completing the milestone of concept development. Nonetheless, the FDC framework incorporates many aspects to help execute these latter stages.

The upcoming chapters discuss the evaluation of the FDC and CEH frameworks and a design tool based on them.



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Chapter 5 Evaluating Frugal Design Conceptualization Framework

The previous Chapter presented the synthesis and details of **Frugal Design Conceptualization (FDC)** and **Context Evaluation Hierarchy (CEH)** Frameworks. These frameworks outlined a systematic approach for designing frugal and holistic design solutions for marginal contexts (MC). This Chapter presents the fourth study of the thesis related to an empirical evaluation of the frameworks. The outcomes of this study highlight the effectiveness of the structured approach based on the synthesised frameworks.

The study followed a 'repeated measures design' where concepts generated using the synthesised frameworks were compared with those generated without them. A set of workbooks was developed, which helped to conduct the conceptualisation exercises systematically. Experts evaluated the concepts generated to identify which ones fared better in a set of subjective criteria. The evaluation showed that experts found the concepts generated using a systematic approach based on the FDC framework were significantly better.

Additionally, the outcomes also helped understand the effectiveness of CEH parameters in the subjective evaluation of design concepts. Concepts generated were evaluated using two sets of subjective parameters by the experts. Checking the correlation between the two-parameter sets suggested that CEH parameters effectively exhibited expert perceptions about a design concept in evaluation. Therefore, since the CEH parameters are more detailed and specific to MC, it makes a good alternative for subjectively evaluating design concepts at early design phases.

The Chapter discusses the key implications of the study and how it affects the frameworks and their implementation. An important outcome of the study was the development of workbooks for systematically implementing the frameworks. These workbooks lay the foundation for developing practical supports based on the FDC and CEH frameworks.

5.1 Introduction and Background

This study's need emerged from the research gaps identified during an extensive literature review on design and innovation for MC. The extant literature review identified guidelines for frugal design and some approaches for designing frugal solutions. In other prior research, requirements for an effective design approach and key design guidelines for frugal and holistic product design were also identified. The major limitation of existing design approaches was that they were relatively abstract, not translated into practically applicable terms and rarely validated empirically. Understanding the strengths and shortcomings of existing approaches led to developing the 'Frugal Design Conceptualisation' (FDC) and 'Context Evaluation Hierarchy' (CEH) frameworks to support systematic frugal design.

One of the primary research objectives in the thesis is to develop an effective systematic approach for designing frugal and holistic solutions for MC. The FDC and CEH frameworks present a way

for developing the systematic approach. This Chapter is concerned with evaluating the effectiveness of the approach. Therefore, the study presented here provide a theoretical validation of the frameworks [1]. Furthermore, the subjective and abstract nature of the frameworks also necessitates theoretical validation. A **Design Conceptualisation Exercise** (DCE) was selected as a process for the study. A DCE process lends well to quantitative scrutiny and can be conducted in a controlled setting to understand the characteristics of a framework.

Based on the identified research gaps and the need for evaluation of synthesised frameworks, a research hypothesis was outlined for directing the study as follows:

Concepts designed using the FDC framework are perceived to be better than concepts designed using a general design approach by experts when evaluating using subjective parameters

The hypothesis clarifies the study's objective and forms the basis for the study design. The statement '*Concepts designed using the FDC framework*' denotes novel design ideas developed using a systematic approach that fulfils the objectives of the FDC framework. This process can be called a design conceptualisation exercise (DCE). In the exercise, designers are given specific contexts and design briefs to generate novel ideas and concepts in a controlled setting. Conceptualisation exercise is a common process followed in design research [2]–[4]. Typically, the outcomes of such exercises are sketches and theoretical descriptions of design concepts which are evaluated using certain parameters established in the research methodology.

The statement '*perceived to be better*' indicates that the evaluation of the concepts is based on '*subjective parameters*'. It is not easy to evaluate the concepts using objective technical performance parameters without extensive prototype testing. Furthermore, there needs to be a sufficient sample size to allow statistical methods to test such a hypothesis. Therefore, prototype testing and technical performance evaluation are inhibitive for a DCE. An evaluation by experts using '*subjective parameters*' was the most appropriate way to check the effectiveness of the designed concepts. However, it should be noted that such a subjective evaluation presents the '*perception of the experts*' and not the absolute performance of the concept.

The subjective evaluation of design concepts can be done using criteria that reflect the requirements and context characteristics. The CEH framework provides a set of specific criteria related to the MC for such evaluations. The framework lists fourteen parameters along which a design solution faces constraints in a marginal context. Thus, solutions that can successfully mitigate these constraints while adequately fulfilling the design brief can be considered good design concepts.

However, it needs to be tested if the expert perception of a solution's effectiveness on CEH parameters is comparable to their evaluation on generic criteria. A similar evaluation by experts would mean that CEH parameters provide an effective means of subjectively evaluating design concepts. Feasibility, Desirability, Viability and Usability parameters have typically been used as general criteria for evaluating design concepts in literature [5]–[7]. In this study, 'Sustainability' is an additional criterion for evaluating the design concepts. Generally speaking, the FVDUS parameters can be defined as follows:

- **Feasibility** indicates the ability to construct and manufacture a design concept.
- **Viability** indicates the ability to produce, sell and create gains from the concept within the financial constraints and resources.

- **Desirability** indicates the ability of the concept to be valuable enough to the end-user that they agree to purchase or acquire it.
- **Usability** indicates the ability of the concept to perform its functions adequately, as expected and with ease to the user.
- **Sustainability** indicates the ability of the concept to perform its function for an indefinite duration without disrupting the ecology or society.

Therefore, the expert evaluation of design concepts when using CEH and FVDUS parameters (Feasibility, Viability, Desirability, Usability and Sustainability) can be compared. Comparable results in the evaluation would mean that CEH parameters are an effective means of subjectively evaluating design concepts. Furthermore, since CEH parameters are related to MC, it provides a contextually appropriate means of evaluating the design concept.

Finally, the statement '*using a general design approach*' presents a way of comparing the design concepts generated using the FDC with a control. This study is concerned with understanding the effectiveness of the FDC framework. It is assumed that the framework is effective if a systematic approach based on the framework produces better concepts than simply following a general design approach. Therefore, '*concepts generated using a general design approach*' represent the benchmark for the FDC framework and the control for the study design. The NPD processes by Pahl et al.[8] and Ulrich & Eppinger [9] are considered the *general design approach* for this study due to the prolific nature of the texts.

It is important to note the effect of established design guidelines when comparing design concepts generated using the FDC framework and a typical design approach. It could be possible that given a generic NPD approach and information about the myriad guidelines for frugal design, designers can develop better concepts than the FDC approach. In such a case, the relevance of the FDC framework may get negated. Therefore, subjects need to know about the various frugal design guidelines when designing concepts using a typical design approach. This way, it is ensured that the effect being measured (better design concepts) results from the FDC framework.

5.1.1 Suitability of Design Conceptualisation Exercise

The primary aim of design research is to develop support and tools for designers to implement in real-life projects [10]. Therefore, the ideal way of validating novel research outcomes in the design field is through an iterative cycle of extensive implementation in real-life projects and reflection. However, such an ideal process can only be followed in a long term research project and is typically out of the scope of a single PhD thesis [10, p. 15]. Design researchers circumvent this by formulating studies of smaller scopes such as workshops, academic projects and experimental evaluations. DCE are one such experimental evaluation process.

There are several strengths to such an exercise. Since such exercises are conducted in a laboratory (or design studio) setting, researchers can monitor the execution of the process more effectively. Incidentally, this also removes noise factors that may contribute to implementing a theory. In the current study, subjects generate design concepts based on a specific design brief. Subjects were given necessary resources (such as internet access) when designing the concepts. In this process, researchers monitored specific tools and additional methods the subjects used.

Additionally, the process provided a clearer understanding of the scope, i.e., the framework phases, which the subjects could implement easily. Thus, the process provided an avenue to gather qualitative data for analysis and insights. The qualitative assessment of the DCE provided an overall understanding of the framework's effectiveness.

Still, some aspects cannot be adequately tested when using such a process for evaluating the FDC framework. For example, employing participatory approaches, first-hand research activities, and interviews with stakeholders were of scope, given the controlled nature of the DCE process. Nonetheless, to partially fill the gaps presented by an absence of participatory approaches, the exercise was conducted in multiple sessions, i.e. in groups and individually. The gaps in lack of first-hand research could be met by providing the subjects with a detailed understanding of design constraints (on CEH parameters) and the user's daily life. Therefore, the design research conducted as part of designing the 'Bicycle Mounted Clothes Carrier' (See Section 3.5) was used as the background for the exercise.

Another argument is that although only an abridged version of the FDC framework can be tested in the DCE tests, its extended version will undoubtedly produce better results. Therefore, any positive results from the DCE will provide meaningful insights and also indicate the FDC framework's overall effectiveness.

5.1.2 Operationalising FDC framework using Workbooks

As previously discussed, the FDC framework is implemented in a design project by developing 'Design Activities'. These are specific steps and tasks executed in a project to meet the objectives of the various phases in the FDC framework. The objectives of each sub-phase in the framework and their envisioned outcomes help create the Design Activities. Table 4.2 (Chapter 4) showed a set of example Design Activities considering a generic frugal design project for MC. The process of conceiving Design Activities based on the time, resources, complexity and scope of a design brief was also discussed in previous chapters. Therefore, a set of Design Activities could be developed specifically for the DCE that meet the exercise's requirements, controlled setting, and design briefs.

Still, developing the Design Activities and presenting them to the subjects during a DCE may not guarantee that all steps are adequately or systematically followed.

The difference between the FDC framework and NPD processes means additional tasks need to be executed when designing effective frugal solutions for MC. Since designers are mostly trained in NPD methods for affluent contexts [11], they may be biased towards executing certain Design Activities in more detail than others. Additionally, designers may not fully understand the relevance of all the Design Activities (e.g. strategic design aspects) for creating holistic frugal design and skip them entirely. Therefore, measures must be taken to ensure the subjects adequately consider all objectives of the FDC framework and execute the Design Activities systematically during the DCE. The workbooks could effectively enable such systematic and curated implementation of design theories during empirical evaluation [12]–[15].

Design workbooks are a way of operationalising theories and are extensively used in design practice [12]–[14]. However, workbooks represent a broad category of tools that range from a collection of related theories translated into practically applicable terms [16] to worksheets that provide ways to conduct speculative design activities [14] to a systematic application of a

methodology using tools [17]. In most cases, the workbooks provide practical knowledge on applying a certain theory, steps that must be executed, and space for executing the steps by sketching, writing or pasting things. A famous example of a design workbook is the 'Wallet Exercise' by Stanford d.School [18], [19]. This workbook operationalises a design thinking approach into a series of worksheets that participants fill with details to meet the overall goal of a design thinking process.

Using a workbook ensured that subjects systematically followed and executed all Design Activities effectively in this study. The workbook could be designed with relevant spaces where subjects record their thoughts and outcomes of Design Activities through sketches, notes and diagrams. The workbook could also clearly illustrate goals and expected outcomes from each Design Activity and relevant FDC phases. Various design guidelines could also be incorporated into the workbook through instructions and checklists. This way, it can be ensured that designers consider relevant frugal design guidelines when executing specific Design Activities during the DCE.

Noting the appropriateness of design workbooks and DCE for the study, a set of Design Activities were developed that could be executed within a specific time frame (3 hours). The time frame emerged out of prior experiences with other concept generation exercises. The Design Activities were then translated into worksheets with instructions and spaces for recording the outcomes. These worksheets and a comprehensive instruction set were combined to form the design workbook, operationalising the FDC framework. Section 5.2.2 gives a detailed account of how the workbooks were developed.

The next section discusses the methodology and various aspects of the study design. Specific details are discussed regarding the execution of DCE, the chosen design context, workbooks developed and measurement methodology. Outcomes of a qualitative evaluation of design concepts are discussed in Section 5.3, which provides interesting insights into the FDC framework's effectiveness. Section 5.4 discusses the outcomes of the experimental study and the statistical tests for the hypothesis.

Finally, the discussion section interprets the results in light of the hypothesis, research questions and lacunae presented earlier. The relevance of the workbook for the development of design support based on the FDC framework is discussed. In conclusion, the limitation of the study is discussed along with possible future work to validate the outcomes further.

5.2 Methodology

Based on the hypothesis, an analysis methodology was selected where design concepts generated using the NPD approach are compared with those generated using the FDC framework. Therefore, two separate concept generation exercises were planned (designated as *NPD-test* and *FDC-test* hereafter). In the *NPD-test*, subjects would work on a specific design brief and generate design concepts using an NPD approach. In the *FDC-test*, subjects would generate concepts using a separate but comparable design brief following the FDC framework. Experts would then compare the outcomes of the *NPD-test* and *FDC-test* to check if there is a difference in some metrics. Thus, the *NPD-test* outcome would work as the control in the experiment.

Figure 5.1 shows the overall methodology followed for the experiment.

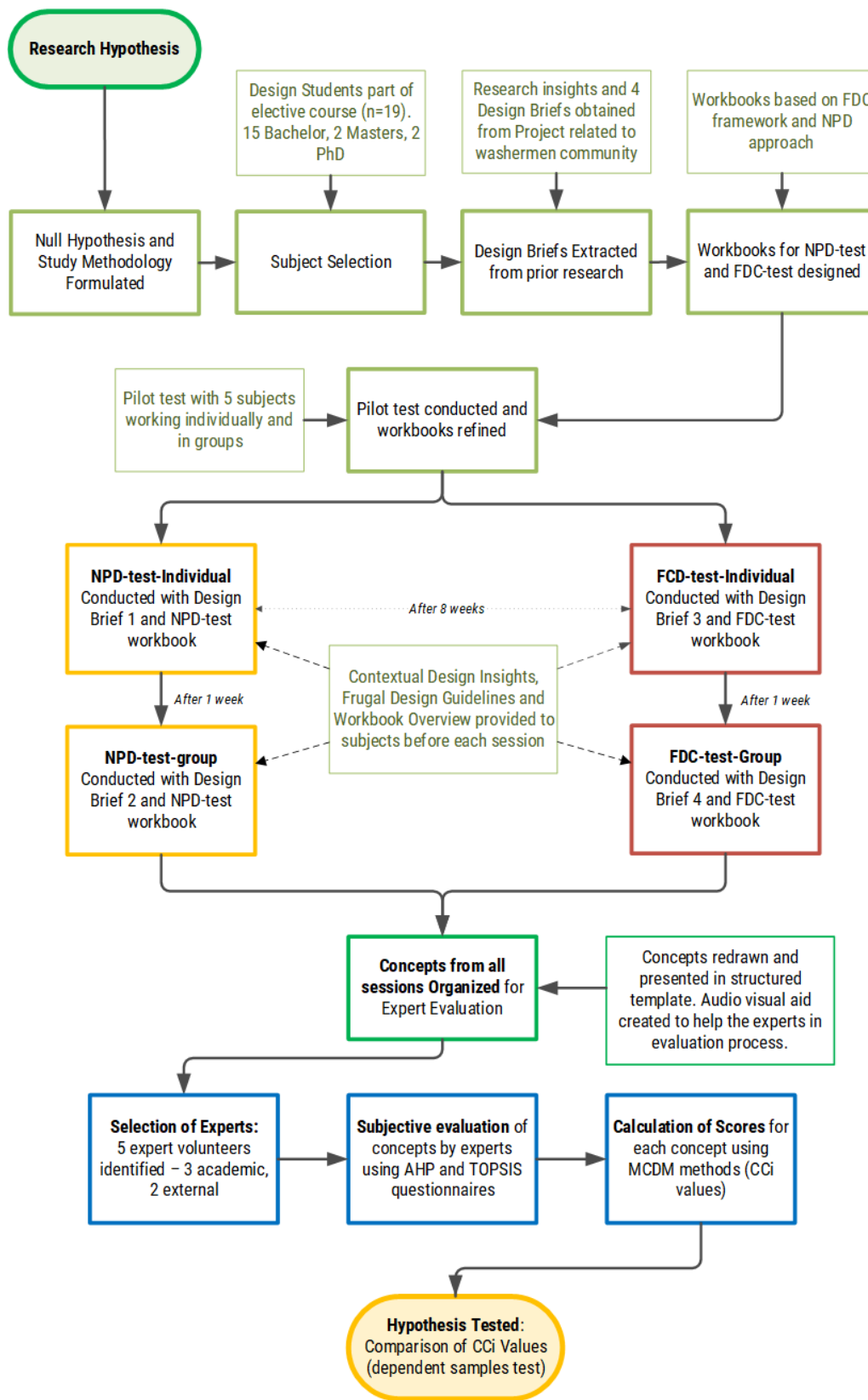


Figure 5.1: Overview of the Methodology followed for the evaluation of FDC and CEH frameworks

Subjects for the experiment were selected from design students enrolled in an elective course at the Department of Design, IIT Guwahati (n=19). The cohort was a mix of PhD (2), Masters (2) and Bachelors (15) students. Since the experiment was concerned with comparing two treatments, subjects did not need to be experts in the design process. However, some degree of familiarity with the design process was needed. Therefore, only final year students from bachelor and master's programs and PhD students who had completed one year in the program were selected as subjects. Additionally, selecting subjects from an elective course ensured some randomness since the course enrolment was voluntary.

It is common practice in design research to select design students as subjects for experimental evaluation of theories [20]–[23]. Selecting design students for research ensures less effect of past experiences on the tests, and the subjects lie at a comparable stage in knowledge and maturity [24]. Furthermore, it allows researchers to administer the treatments more uniformly and identify the common difficulties that novice designers may face with particular theories.

The study design is thus a 'repeated measures design' with a non-random subject selection, making it a quasi-experimental analysis [25], [26]. However, there have been some reports with claims of causality when following a similar repeated measures study design [20].

A repeated measures study design was found appropriate considering several reasons. Nevertheless, first, it should be acknowledged that a randomised control experimental setup would undoubtedly be the best way to assess the hypothesis. However, this requires access to a sizable number of randomly selected design practitioners. Unfortunately, this is difficult in the design research context since practising designers have less time to spare for multiple extensive DCE sessions over a long duration [21]. Therefore, design students were chosen as subjects. Additionally, the sample size was also small due to the time commitment needed from subjects. Larger sample sizes are needed for the generalizability of findings.

Fortunately, repeated measures design provides a suitable way to handle scenarios with limited subjects, especially when the research focuses only on comparative effects of treatments [27]. Albeit inferences from such studies have to be carefully derived. Still, the study design has effectively been used in many design-related research publications [20], [24], [28], [29]. The study is also suitable since the outcomes can be analysed using dependent-samples t-tests and repeated measures ANOVA to objectively compare the group performance between treatments.

After finalising a 'repeated measures design' and subject selection, the next step was to plan the NPD-test and FDC-tests. One of the concerns discussed earlier was the effect of participatory idea generation in the FDC framework. Thus, two separate sessions each for NPD-test and FDC-test were planned to partially understand the effect of collaborative ideation. The assumption was that, since there exists some evidence of participatory approaches improving the quality of concepts [30]–[33], implementing participatory approaches will not reduce any proven effectiveness of the FDC framework.

The first session of the NPD-test was conducted with subjects working individually, and the next NPD-test session had them working in groups. Similarly, two sessions of the FDC-test were conducted with subjects working individually and in groups. Thus, a total of four DCE sessions were conducted (designated as *NPD-test-individual*, *NPD-test-group*, *FDC-test-individual*, *FDC-test-group*). The group sessions could be compared to each other to understand how well the FDC framework worked in co-design. In contrast, group and individual sessions could be compared to understand the effect of collaborative ideation using the FDC framework.

For each of the four sessions, a design brief was outlined from the research project related to the washermen community (see section 5.2.1). Each design brief was carefully reviewed and evaluated by experts to ensure that they presented similar complexity levels and that the expected work could be completed within a similar timeframe. Each DCE session was planned to be three hours long based on a pilot test where subjects solved a similar complexity design brief.

Next, two design workbooks were developed, one for the NPD-test and one for the FDC-test. The workbooks enabled subjects to systematically follow the various steps and Design Activities during the DCE sessions. The NPD-test workbook was designed based on a typical design approach [8], [9], whereas the FDC-test workbook followed the specific Design Activities based on the FDC framework. Section 5.2.2 below discusses the development of the workbooks in detail.

After developing the first version of the workbooks, a pilot test was conducted with six design students (three Bachelors working in a group, two masters students working individually and one PhD researcher working individually). A design problem similar to the ones planned for the DCE sessions was used for the pilot test. Participants of the pilot test were different from those selected for the experiment. The participants in the pilot test were interviewed after completing the exercise to understand the difficulties faced in implementing the workbooks. Both the NPD-test and FDC-test workbooks were then iterated based on the outcomes of the pilot test and were later used in the DCE sessions.

The four DCE sessions were conducted after completing the subject selection, workbook design, and pilot tests. Each DCE session lasted for 3 hours. The key challenges in repeated measures design are due to order effect and practice effects [34]. To ensure that such effects were minimised, the NPD-tests and FDC-tests were temporally spaced with a gap of nearly eight weeks. Alternatively, the individual and group sessions for each related test were done in temporal proximity of 1 week. Thus, two sessions for NPD-test (individual and group) were conducted first in a gap of 1 week. After a break of around eight weeks, the two FDC-tests were similarly conducted with a one-week gap between individual and group sessions. During the eight-week gap, subjects were intellectually engaged in other activities, due to which we assume the effects of one test on the other were further minimised.

Before each DCE session, subjects were given a briefing in the form of a presentation. The presentation contained the details of research outcomes and insights from the project on the washermen community. Design insights relevant to each CEH parameter were provided, along with the general overview of the MC. In addition, a summary of the frugal design guidelines (Appendix A) was provided. The presentation also contained a brief overview of the workbook for the session and the design brief.

In each DCE session, subjects generated design concepts for a specific design brief and recorded the details in the relevant workbooks. Volunteers were available during the exercise to clarify any doubts. After completing all sessions, the outcomes were reviewed, and qualitative analysis of the generated concepts was done.

After a qualitative analysis, the design concepts were given to five expert volunteers for evaluation. Experts were selected based on their experience in designing frugal solutions for MC. Three expert volunteers were from an academic background, and two were award-winning grassroots innovators and entrepreneurs who had prior experience designing frugal solutions. The generated concepts were appropriately organised to reduce biases in subjective evaluation by experts (See section 5.2.3).

The subjective evaluation of the concepts was done using a multi-criteria-decision-making (MCDM) method. MCDM are a set of decision making mathematical tools that can be used to evaluate concepts based on subjective criteria [35]. The 'rough group-AHP' and 'rough group-TOPIS' MCDM methods proposed by Song et al. [35] were followed for expert evaluation of each concept (see section 5.2.4). Following the calculations in MCDM resulted in a measure called 'Closeness Coefficient' (CCi) for each concept [35], which indicates the merit of a design concept compared to all others in a set.

The subjective parameters chosen for evaluation were based on the CEH framework and FVDUS (Feasibility, Viability, Desirability, Usability and Sustainability). The CCi values obtained from MCDM methods presented a ratio scale that could be analysed using appropriate statistical tests for testing the hypothesis. The difference-of-mean of CCi values between concepts generated in the NPD-test and FDC-test was used to infer the experiment results. A paired dependent samples Student's τ test, Wilcoxon signed-rank test and repeated measures ANOVA test were conducted to test the hypothesis

The Closeness coefficient values considering CEH and FVDUS parameters were also separately calculated for each concept. Comparison of these CCi values provided insights on the expert perception of the CEH parameters. The key insight tested was whether experts perceived CEH values similarly to FVDUS parameters when subjectively evaluating the concepts. Table 5.1 shows how the hypothesis was interpreted and operationalised for the study.

Table 5.1: Null Hypothesis and operationalisation

Hypothesis	Null Hypothesis	Operationalisation
<p>Concepts designed using the FDC framework are perceived to be better than concepts designed using a general design approach by experts when evaluating using subjective parameters</p>	<p>There is <i>no difference</i> in the subjective evaluation scores (CCi values) obtained by,</p> <p>Concepts designed using the FDC framework,</p> <p>And concepts designed using a general design approach.</p>	<p><i>Independent variable</i>: Approach Followed (NPD-test workbook or FDC-test workbook)</p> <p><i>Dependent variable</i>: Evaluation Scores (CCi value using CEH parameters and CCi values using FVDUS parameters)</p> <p><i>Study design</i>: Single-group repeated measures</p> <p><i>Method</i>: Comparison of CCi scores obtained through MCDM evaluation in subjective criteria. (dependent samples t-test, Wilcoxon signed-rank test)</p>

The detailed execution of the experiment considered several aspects to reduce biases during various steps and improve the study's internal validity. These specific aspects are discussed in the sub-sections below.

5.2.1 Problem statements and Design Context

The insights and research data collected during the project on 'designing a bicycle mounted clothes carrier for washermen community in Guwahati' (Section 4.3) were used for developing the problem statements.

The project was chosen due to the richness of the research data collected. Various research methods were conducted during the project, such as semi-structured interviews, participatory research sessions, focus group sessions, observational studies and analysis of work practices. Specifically, the project intended to design and develop solutions that reduce physical effort during the washing process, increase customer base, improve customer management and reduce health and environmental hazards for the washermen community. The research results led to identifying several design opportunities, insights and project briefs. Four design briefs were selected for the DCE from the project's research outcomes.

The briefs for DCE sessions were based on four specific design opportunities 1) design of a workspace for washing clothes near river banks with effective waste disposal methods, 2) intervention for helping reduce physical efforts while removing hard stains from clothes, 3) intervention for easy rinsing and removal of water from wet clothes, and 4) intervention for carrying and transporting heavy bundles of wet clothes. Some of the problems observed in the context relevant to the design opportunities can be seen in Figures 5.2 to 5.7.



Figure 5.2: Washermen have no space for working. They use rocks to beat the clothes on. The clothes are beaten to remove hard stains and requires much physical effort.



Figure 5.3: Washermen use their feet to rinse clothes. Waste plastic detergent packets can be seen strewn on the river bed. They face skin problems due to continuous exposure to hard chemicals.



Figure 5.4: The clothes are rinsed by twisting them. This strenuous repeated action combined with bad posture causes health problems. The wastewater is disposed of directly in the river.



Figure 5.5: The process of removing hard stains is physically demanding. The washermen are culturally habituated to use current working practices and tools and find it difficult to accept change



Figure 6: The feet of washermen show signs of skin problems due to constant exposure to chemicals and detergents. They face other health issues due to their working practices and bad posture.



Figure 5.7: The washermen transport washed clothes in bundles. They bring detergent soaked clothes to the river bank for washing and rinsing and carry the washed clothes for drying. Each bundle of wet clothes can weigh up to 80 kgs.

Based on the opportunities identified, the following design problems were formulated for each of the DCE sessions:

- **For NPD-test-Individual session:** “Design **a method for removal of hard stains from cloths** and make the work of users easier considering the activities that they do at the river banks.”
- **For the NPD-test-group session:** “Design **a workspace** to make the work of users easier considering the activities that they do at the river banks.”
- **For the FDC-test-individual session:** “Design **a method for transportation and carrying of clothes** and make the work of users easier considering the activities that they do at the river banks.”
- **For the FDC-test-group session:** “Design **a method for removal of excess water from recently washed clothes** and make the work of users easier considering the activities that the Dhobis do when they are at the river banks.”

Only the bold underlined parts of each design problem were changed to reduce biases due to problem statement formulation [36]. Since the overall context for each problem is similar and there were large overlaps in insights, the concepts generated for each problem would be comparable using similar subjective parameters.

The detailed research from the project was also organised and used in two specific instances. Firstly, all the insights generated from the project research was organised based on each CEH parameter. Before beginning each DCE session, this research was presented to the participants (See **Appendix E**). Additionally, design insights relevant to the specific problem statement of the DCE session were also presented to the subjects before beginning the session. The briefing session before each DCE session lasted for nearly 30 minutes, followed by a discussion to clarify any doubts subjects had. The briefing session simulated the first phase of the FDC framework related to ‘gaining a deep understanding of the context’.

Second, the research was used to develop an orientation video for the experts. This orientation video summarised the research with the details of CEH parameters and the design problems. The video was played for experts before they evaluated the concepts and filled the AHP questionnaire (See **Appendix E**). The orientation video was developed to reduce biases in subjective evaluation arising due to unequal understanding of the context among experts.

5.2.2 Design of test workbooks

Two workbooks were developed for supporting the DCE Sessions. The first was the NPD-test workbook based on a typical product design and development approach derived from prominent design literature [8], [9]. The NPD-test and its outcomes were considered as the control for the experiment.

Appendix C shows the NPD-test workbook. The workbook contained instructions to generate as many ideas as possible and present a single final solution for the design brief. Subjects were told that the concepts would be evaluated on overall quality and clarity of communication. Instructions were also given for each of the four steps, and subjects were asked to follow them sequentially. Separate sheets were provided to make notes, sketch the concepts, and present the final solution.

In addition to general instructions, a list of guidelines for frugal design was also provided in the NPD-test workbook. Subjects were asked to use the guidelines as prompts to support ideation. The guidelines were derived from the extant literature review (**Appendix A**). Having access to the guidelines ensured that the subjects knew the information when generating the concepts. Therefore, any difference in the concept scores would result from following the process and not due to a lack of information. The NPD-test workbooks were designed to be more open-ended to reduce fixation to any specific type of solution.

The workbook for FDC-test was based on the FDC framework. It was specifically designed to ensure subjects minutely considered the holistic aspects in frugal design for MC. A set of Design activities were devised that met the major objectives of the framework's phases considering the time limit and scope of the DCE. The workbook was created so that the subjects could execute the Design Activities systematically. Table 5.1 shows the Design Activities considered for the DCE and their implementation in the workbook. The detailed workbook is shown in **Appendix C**.

Table 5.2: Design Activities implemented in the FDC-test workbook.

FDC Framework Sub Phases	Design Activities considered for DCE	Implementation in FDC-Test Workbook
Initiation	Clarification of Design Brief	Detailed information regarding the context, users daily lives and design brief were provided to subjects before the session. The briefing can be considered as a simulation of these FDC sub-phases.
Context Understanding	Understanding the work practices Understanding the work context	
Problem Definition	Analysis of the research work Redefining the project brief	Step 1: <i>Reframe the Problem statement</i> into a Product and Services oriented statement Step 2: Write the <i>Requirements</i> for the Product and Services
Product Design Ideation	Generate Product design Ideas	Step 3: Generate as <i>many ideas</i> as possible.
Solution Proposal Ideation	Generate strategic design Ides Identify existing solutions Select compatible design ideas Formulate holistic solution	Step 4: Select and combine a set of ideas and make the holistic solution Step 5: Generate a Systems configuration for the solution in use
Product Design Definition	Develop product architecture Develop product embodiment Assess compatible strategic design ideas	Step 6: Generate a <i>product architecture</i> diagram for the concept. Step 7: Detail out the <i>critical sub-components</i> Step 8: Generate the <i>second iteration of the Systems configuration</i> for the solution
Solution Proposal Definition	Develop payment model and strategies Develop distribution and dissemination strategies Develop Service and maintenance design strategies Develop strategies for upgrading the	Step 9: Design a Systems map with ' <i>Product being made</i> ' Step 10: Design a Systems map with ' <i>Product being disseminated</i> ' Step 11: Design a Systems map with ' <i>Obsolete product</i> '.

	solution Develop Strategies for managing the end of life Iterate product design to support solution proposal	Step 12: Design a Systems map with 'Useless product'. Step 13: List down <i>new ideas for product design</i>
Proposal Formulation	Create communication for the solution	Step 14: Create a <i>flow diagram</i> to show how the solution will be used.
Downstream Planning	Create an initial plan for solution deployment	Step 15: Make an <i>Offering map</i> for the final proposed solution.

Each step in the workbook contained specific instructions related to its execution, envisioned outcomes and frugal guidelines related to the particular step. This way, it was ensured that designers had information on relevant design guidelines during each step. Figure 5.8 Shows the instruction sheet for one of the steps in the workbook. The workbook had 15 steps for the subjects to execute without specific time limits for each step. However, subjects were encouraged to monitor the time spent on an individual step and review all the steps when conducting the exercises.

The workbook had designated spaces for recording the outcomes of each step. These spaces contained additional annotations, prompts and structured space to note or draw their ideas. Such a structured space forced the subjects to think and produce outcomes expectedly. For example, Figure 5.9 shows an example of a worksheet with the space provided for recording the outcomes of step 8. (See **Appendix C**)

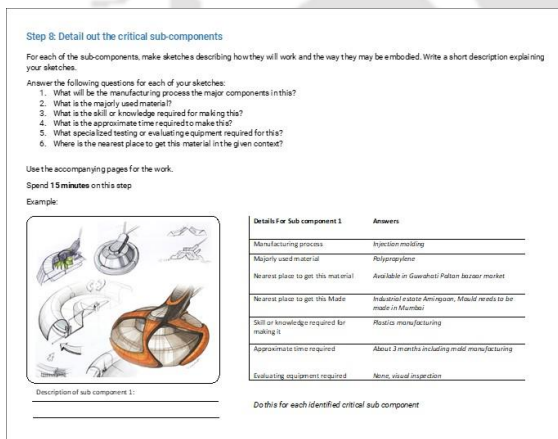


Figure 5.8: A page from the FDC-test workbook showing the layout. The page contained instruction and examples of what was expected from the subject. Examples were unrelated to design problem.

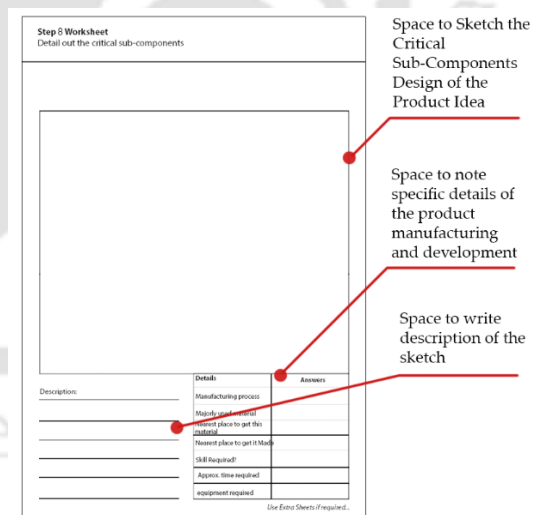


Figure 5.9: A page from the FDC-test workbook showing the structure provided for recording details of critical sub-components of the product.

There were several other ways in which the FDC-test workbook differed from the NPD-test workbook:

- 1 The number of steps in the FDC-test workbook was much higher, and subjects were encouraged to complete all steps within the stipulated time limit.
- 2 The FDC-test workbook had examples for most of the steps. These examples were used for explaining the expected outcomes when subjects faced difficulties in a certain step.
- 3 The subjects recorded their work on the workbook itself. Space was provided with relevant information, annotations and demarcated areas for sketching and recording their thoughts.
- 4 The instructions and the space provided were created considering the objectives of the FDC framework phases.

Before using the FDC-test workbook in the experiment, experts scrutinised it to check if it adequately reflected the FDC framework.

Additionally, the first iteration of the workbook was used in a pilot test to check if it could be executed within the time limit. The pilot was conducted with five different subjects. Three subjects worked in a group, and two worked individually using the FDC-test workbook. The volunteers were allotted a three-hour time for completing the first iteration of the workbook. After completing the exercise, a focus group was conducted to record their views. The goal of the pilot test was to understand the difficulties and identify necessary changes to the first iteration of the workbook. The outcomes were discussed with experts to check if volunteers adequately followed the FDC framework.

Overall the pilot volunteers felt that the process was better than a generic product design exercise. However, some changes were suggested that were then incorporated into the final version of the workbook presented here. For example, they suggested that some steps needed examples and detailed explanations on how to execute. Thus, examples were included with the workbook steps, and in the pre-exercise briefing, these were explained to the experiment subjects. The final workbook used in the experiment was thus modified with additional details based on the pilot test.

5.2.3 Subjective Multi-Criteria decision making and evaluation of concepts

Design concept evaluation can be done using a multi-criteria decision-making (MCDM) approach [37]. In the early stages of product design, it is difficult to use precise data sets (crisp data sets) such as cost, time to manufacture, etc., to evaluate a concept [37]. It is possible to subjective criteria at such early stages. However, the nature of such evaluation is inherently vague if typical concept evaluation methods are used [37], [38]. Fuzzy sets and rough-group sets can describe the evaluation data and handle such inherent vagueness to mitigate such issues. [35], [39].

Since the concepts generated in DCE do not have objective performance indicators, and the outcomes can be considered early design phase concepts, a subjective evaluation made the most sense. Moreover, the CEH and FVDUS parameters chosen for concept evaluation can only support assessment in linguistic terms. Therefore, MCDM methods were found to be most appropriate and were chosen for the expert evaluation.

There are various types of MCDM available from various domains. Shidpour et al. [37] provide a list of various MCDM methods used in mathematics and artificial intelligence literature employed for decision making. More and more researchers suggest using hybrid MCDM methods to

accommodate the vagueness in subjective evaluations [37], [40], [41]. Among the hybrid methods, fuzzy set theory and rough group set theory are commonly integrated with MCDM methods.

Certain Non-numerical methods for concept evaluation also exist, such as those proposed by Ulrich and Eppinger[9] and Pugh [42], which help in simple and quick concept evaluations. However, these methods work best only when the evaluation criteria are objective, the number of criteria is less, and concepts are generally less complex [37], [41]. On the other hand, MCDM methods are systematic, accurate, and scalable to complexity [43].

A rough-group based MCDM was suitable for this study since it considered the inherent vagueness of evaluation, experts propensity to risk and required relatively less effort [37]. Therefore, the hybrid rough-group set based MCDM approach suggested by Song et al. [35] was selected. An added benefit of Song et al.'s approach is that the outcome is a crisp value which can be considered the score obtained by a concept after expert evaluation. This crisp value can be used for conducting statistical tests for the hypothesis. Song et al.'s approach was suitably adapted for the DCE evaluation and is presented in **Appendix H**.

The approach uses a hybrid approach where Rough-group based AHP is used to generate the weights of each CEH parameter. The concepts are then evaluated using a Rough-group based TOPSIS method. Therefore, the process requires two specific questionnaires, one for AHP and one for TOPSIS. Both these questionnaires are administered to the experts evaluating the concepts. The AHP questionnaire used in the experiment is shown in **Appendix F**, and the TOPSIS questionnaire in **Appendix G**. Each expert answered one AHP questionnaire before starting the concept evaluation. In contrast, the TOPSIS questionnaire is answered by each expert for every concept that is evaluated.

The approach uses Rough-sets to accumulate the evaluations of five experts and make the calculations. Therefore, the risk propensity and variations in evaluation are reduced. An overview of the chosen methodology is given below, and the detailed process is presented in **Appendix H**.

5.2.3.1 Rough-group AHP and TOPSIS method

The AHP process was first proposed for MCDM by Saaty in 1987 [44] as a general measurement theory and requires a hierarchical organisation of evaluation criteria similar to that presented in the CEH framework. In the process, each criterion is evaluated in pairs to determine the relative importance between them on a scale of 1 to 9. This pair-wise comparison generates the relative weights of each criterion which are then used for the concept evaluation.

AHP method can also be used for evaluating the concepts, but the process requires comparing pairs of concepts with each other. Since the DCE resulted in 46 concepts, it would be impractical to consider AHP for expert evaluation¹. Therefore, the TOPSIS method was suitable.

In comparison, The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is good for concept ranking due to its simplicity and ability to consider a non-limited number of concept alternatives [45]. It is used to rank a set of alternatives according to their distances from a theoretical 'ideal positive' and 'ideal negative' solution [46]. These Ideal solutions are the set of values obtained from the concepts being evaluated. The Ideal solution is a hypothetical construct of an alternative with the best values in all the criteria, and the negative

¹ $C_2^{46} = 1035$ pairs would have to be evaluated if the AHP process itself was also used for concept evaluation.

ideal solution is an alternative with the worst. The ideal solutions are derived from the available alternatives after being evaluated based on the criteria.

TOPSIS has been successfully applied to solve selection/evaluation problems due to its simplicity and intuitiveness. It is also seen that the TOPSIS method can circumvent the problems of the weighted sum method [47]. Furthermore, it has been seen that TOPSIS can effectively represent the rationale of human choice [48].

The concept of using rough set theory in MCDM methods was proposed by Zhai et al. [43]. In their conception, a 'rough number' denotes the vagueness or fuzziness of a crisp number with upper and lower bounds. Thus, the rough number is an interval with boundaries within which the true number lies. For this study, a rough number could better reflect the perceptions of multiple experts when subjectively evaluating a concept. The lower and upper bounds of the rough number will depend on how various experts answered a particular evaluation question. **Appendix H** presents the details for calculating rough numbers and their use in AHP and TOPSIS methods. In essence, the AHP and TOPSIS methods are executed by replacing the crisp numbers with these rough numbers.

Finally, In Song et al.'s [35] proposed process, rough numbers are used for both AHP and TOPSIS calculations (thus named Rough-group AHP and TOPSIS). They provide a means of converting the resulting rough number outcomes from TOPSIS into a crisp number called the Closeness Coefficient (CCi). This CCi value was then used for testing the hypothesis. Since the calculations involved were elaborate and required multi-dimensional matrix manipulations, a MATLAB® script was developed to help with the process (See **Appendix I**).

5.2.4 Overall Study Design

Two tests were conducted with subjects working individually, one using the NPD-test workbook and one using the FDC-test workbook. In both, the individual tests subjects worked without communicating with other members in an examination hall. While conducting the individual sessions, volunteers closely monitored the subjects and cleared necessary doubts and provided additional relevant information about the context. However, volunteers refrained from suggesting new ideas or indicating a preference for certain ideas.

Similarly, two sessions were conducted with subjects working in groups. In both the group sessions, subjects worked in a group of five in a studio setup. The groups were not changed between the NPD-test and FDC-test to ensure that the concepts generated by the groups could be compared. Subjects were briefed about the nature of the experiment and the time commitment before recruitment into the DCE. Due to the intensity of the exercise, subjects were incentivised through reduced attendance requirements for participating in the experiment.

Before starting each session, the research insights related to the design context were recapitulated, and details specifically related to the design brief of the session were explained. Additionally, the workbooks were also explained in detail. While explaining the workbooks, the intended outcomes, the evaluation criteria and the relevant frugal design guidelines were also highlighted.

Sheets of paper were provided for recording ideas, sketching and notetaking in the NPD tests, whereas a structured booklet was provided for the FDC test (**Appendix C**). Subjects were

encouraged to utilise all of the 3-hours for generating concepts during the sessions. After completion of each session, the submissions were scrutinized, and outcomes were briefly discussed with the subjects. Qualitatively speaking, the NPD-test outcomes spanned 7 to 12 pages, whereas the FDC-test outcomes spanned 12 to 20 pages (higher page counts were observed in group sessions). A total of 46 concepts were obtained from the four DCE sessions.

After completing the exercise, the concepts generated were collected and prepared for expert evaluation. It was observed that visual representation quality varied amongst the outcomes due to the subjects sketching ability. Moreover, the information relevant for effective evaluation was scattered throughout the submissions. It would have been challenging for experts to evaluate each concept which spanned 10 to 20 pages. Moreover, the variation in sketch, annotation and language quality could bias the evaluation.

Therefore, an illustrator was enlisted to redraw the concept sketches on an individual page to reduce biases due to subjects' sketching ability. Similarly, written material provided by the subjects was reviewed and structured on a single page template. The structuring was done to highlight specific details needed for expert evaluation of the concepts. Thus, a two-page summary for every concept was created, with one full page of sketches and another page with textual details.

Appendix D Shows the two-page summary of two of the concepts generated during the session, two-page summary sheets for all 46 concepts were similarly created. When developing the textual details, the information was not interpreted, i.e. it was ensured that only the information explicitly mentioned by the subjects was incorporated in the two-page summary.

Additionally, compared to the NPD-test workbook, the FDC-test workbook was more elaborate to help subjects consider the holistic aspects of the solution more minutely. Due to this, more information was generated by subjects using the FDC-test workbook. It was recognised that the quantity of information could bias the evaluators, so restructuring the information in two-page summary sheets was necessary. The two-page summary ensured that the concepts were presented to experts in a similar structure and minimised information overload. This way, it was ensured that the comprehensiveness of the FDC-test workbook did not bias the expert evaluation.

Finally, A booklet containing the two-page summary of the 46 concepts was created for evaluation by experts. The order of the concepts in the booklet was also randomised to reduce any sequencing bias in evaluation. Overall, 46 concepts needed to be evaluated on 24 subjective criteria (considering CEH and FVDUS parameters).

The evaluation was done with the help of 5 expert volunteers who had significant experience in developing products and solutions for the MC. The choice of experts was made through targeted sampling based on their area of expertise, years of experience in designing for MCs and familiarity with the selected MC. Of the five experts, three were chosen from academia with over five years of experience designing solutions for MCs in an academic setting. All three had supervised and individually worked on design projects related to marginal contexts.

The other two experts were non-academic. These experts were award-winning grassroots innovators who had developed, produced and were currently selling products aimed at MCs. Both experts had received the president's award for their grassroots innovations and several other accolades for their work. Experts were chosen from in and around Guwahati to ensure their familiarity with the context.

Experts had to fill two separate questionnaires related to the chosen MCDM methods to evaluate the concepts. The first was the AHP questionnaire (**Appendix F**), and the second was the TOPSIS questionnaire (**Appendix G**). A pilot test of the evaluation questionnaires was done to understand if experts could follow them satisfactorily. Two experts helped with the pilot testing the questionnaires (both were not part of the main concept evaluation). They were then interviewed to understand the difficulties faced and the changes needed.

The pilot evaluation highlighted that the questionnaires were complex. Thus, a paper-based evaluation mode was chosen. Furthermore, experts found the written material for understanding the details of the MC overwhelming. They felt that audio-visual material for understanding contextual details before the evaluation was needed. Therefore, a video presentation was created to brief the experts about the context before starting the concept evaluation (See section 5.2.1 and **Appendix E**). Additionally, the video briefing ensured that all the experts had a similar understanding of the MC before they commenced concept evaluation.

The booklet with the two-page summary of 46 concepts was then given to five selected experts for evaluation along with the AHP and TOPSIS questionnaire. The video briefing was played for each expert before administering the AHP questionnaire. Experts then assessed the concepts using a two-part TOPSIS questionnaire (**Appendix G**). The first part asked the experts to evaluate the concepts based on general qualitative parameters of perceived Feasibility, Viability, Desirability, Usability and Sustainability (FVDUS). The second part asked the experts to evaluate the concepts based on the CEH parameters.

Many subjects did not explicitly mention details relevant to all CEH or FVDUS parameters in their concepts. Therefore, experts were asked to use their prior experience to judge the concept and score it on all of the CEH and FVDUS parameters, even if no specific information was mentioned in the two-page concept summary.

The expert evaluation resulted in a data set as per the selected MCDM approaches. A MATLAB® script (**Appendix I**) was used to execute the MCDM approach [35] and generate the scores for each concept (CC_i). Specifically, two CC_i scores were obtained from the evaluation, one based on the CEH parameter (CC_{iCEH}) and one based on the FVDUS parameters (CC_{iFVDUS}). Dependent-samples statistical test using CC_i value was used to test the hypothesis. Also, a correlation between CC_{iCEH} and CC_{iFVDUS} was checked to see if CEH parameters produced similar results in subjective evaluation compared to FVDUS parameters. Concepts were also qualitatively analysed to understand how they considered various frugal design aspects.

5.3 Qualitative assessment of DCE outcomes

Figures 5.10 to 5.13 below show some of the outcomes submitted by subjects in the four DCE sessions.

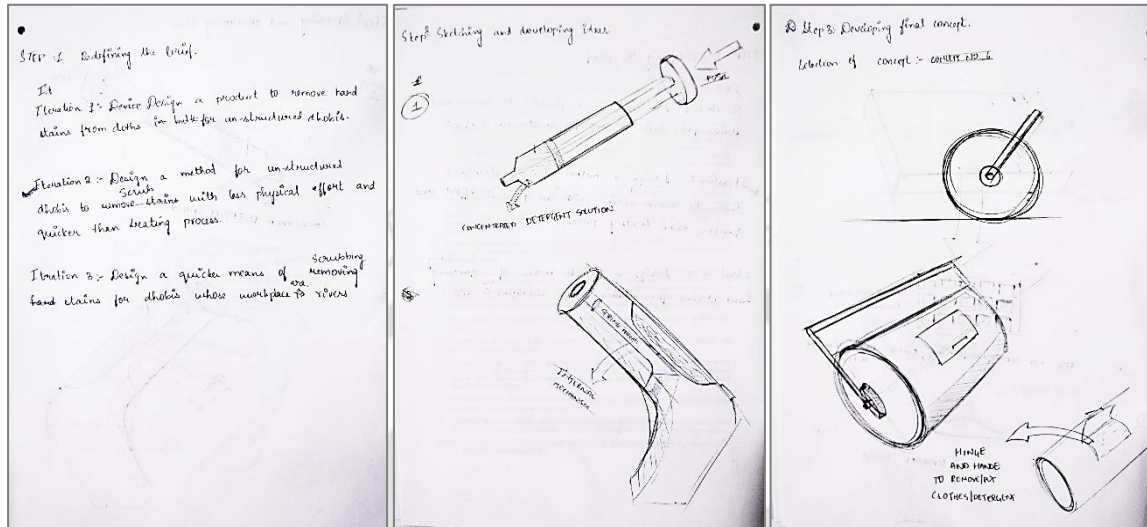


Figure 5.10: Some pages showing how design concepts were generated during the NPD-test with individual subjects.

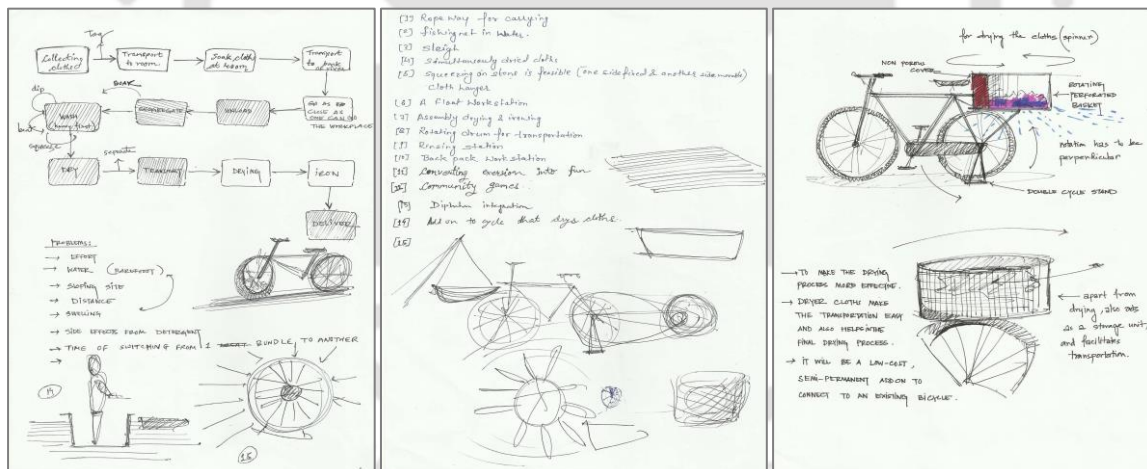


Figure 5.11: Some pages showing how design concepts were generated during the NPD-test with subjects working in groups.

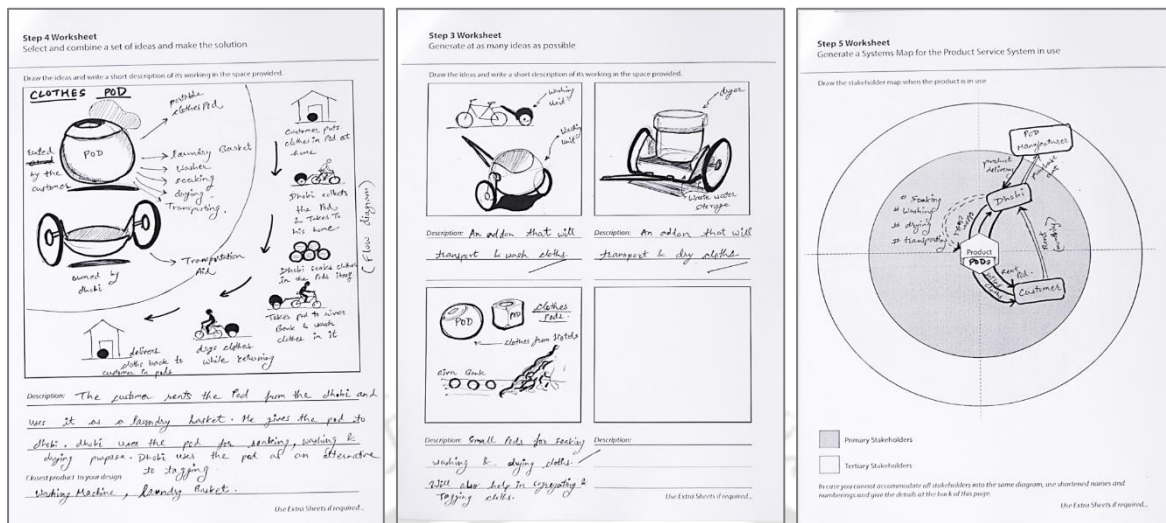


Figure 5.12: Some pages showing how design concepts were generated during the FDC-test with individual subjects.

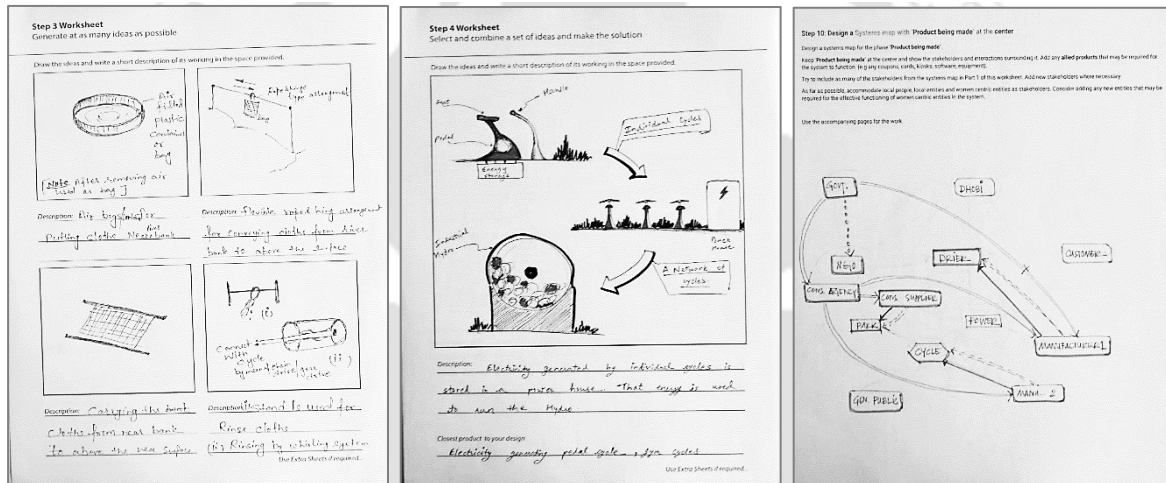


Figure 5.13: Some pages showing how design concepts were generated during the FCD-test with subjects working in groups.

After collecting the outcomes, a qualitative evaluation of the submissions was done to understand the outcomes in the four DCE sessions. The MCDM based subjective evaluation by experts only concentrated on the final solution presented by subjects. Due to this, many specific details noted in the submission were not explicitly part of the expert evaluation. For example, subjects generated several rough ideas before finalising the design concept. These rough ideas were not the basis of expert evaluation. Nonetheless, the number of ideas subjects could generate in a session also provides crucial clues about the process followed.

Similarly, subjects were encouraged to note down strategic details for supporting the solution in marginal contexts in all four sessions. These strategic details were then summarised in the textual part of the two-page concept sheet for expert evaluation. A qualitative evaluation of these strategic decisions could also provide interesting insights into the process followed. Based on these arguments, a qualitative assessment of the outcomes was first completed before the hypothesis tests.

The submissions were qualitatively evaluated to find: 1) the number of ideas generated in the sessions, 2) how the concepts considered FVDUS and CEH parameters, 3) how the concepts considered product lifecycle stages, and 4) if the concepts considered any frugal design guidelines. Each submitted document was reviewed, and data were collected based on the description and sketches presented by the subjects. The charts presented below show the findings of the qualitative evaluation.

Figure 5.14 shows the average number of distinct ideas generated in each session. As shown, on average, the number of ideas generated in each session was similar, except for when the concept generation was done in a group using the FDC-test workbook. In the group NPD-test the total ideas generated were 23 (n=4, mean= 5.8, sd= 3.9). In the FDC-test, the same groups generated a total of 58 Ideas (n=4, mean=14.5, sd= 2.4). Overall it seems that the FDC workbook did enable collaborative ideation. However, there could be other reasons for the difference, such as a better understanding of the workbook after the individual session and improved group dynamics in the latter sessions. Nonetheless, the effect on ideation using the FDC framework is promising, but it needs to be studied separately.

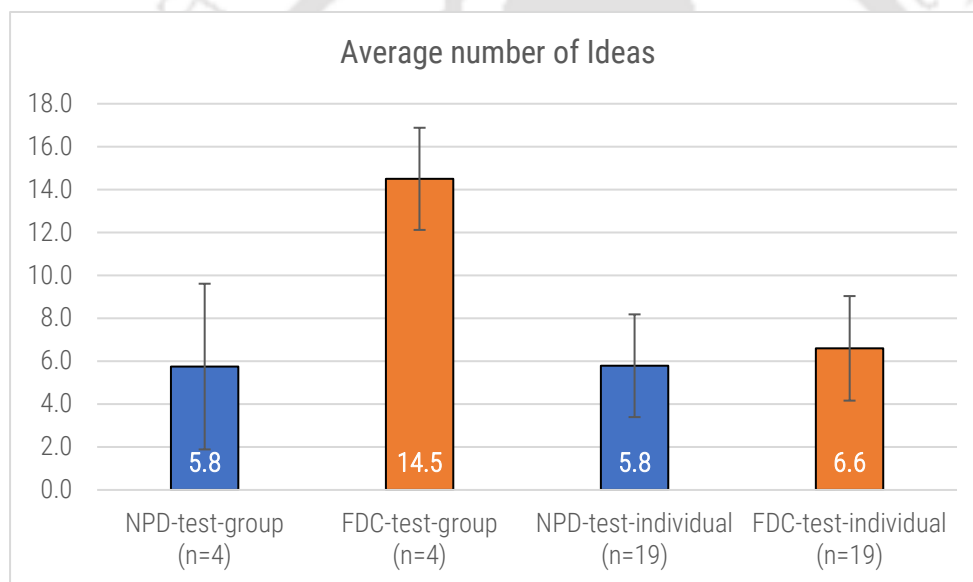


Figure 5.14: Average number of ideas generated in each DCE session

Next, the final concepts from each DCE session were analysed. It was important to understand if the concepts could be evaluated using the FVDUS parameters. Figure 5.15 shows how many concepts considered FVDUS parameters. This analysis was done by searching for information related to each FVDUS parameter mentioned by the subjects in the submitted workbooks.

It can be seen that during both the NPD-test and FDC-test, the final concepts generated nearly equally considered aspects related to FVDUS parameters. Therefore, this clarifies that the experts would have sufficient details on FVDUS parameters for an effective evaluation.

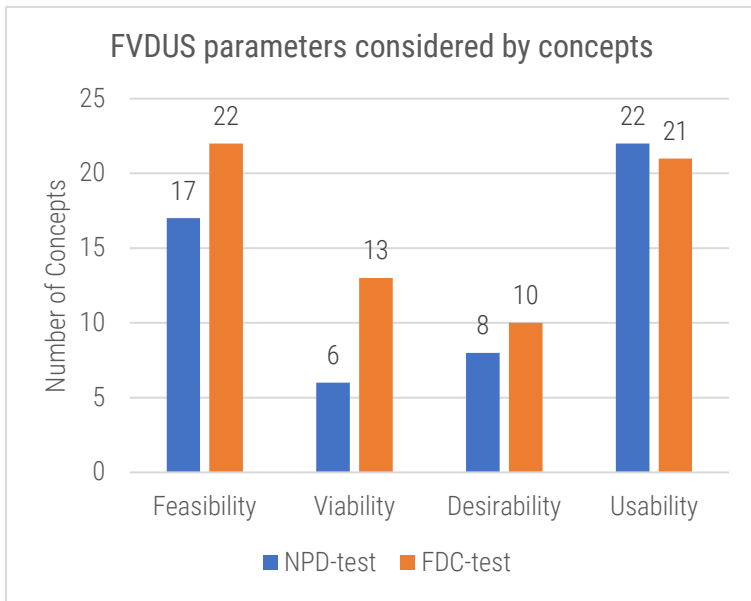


Figure 5.16: Number of concepts that considered aspects related to FVDUS parameters

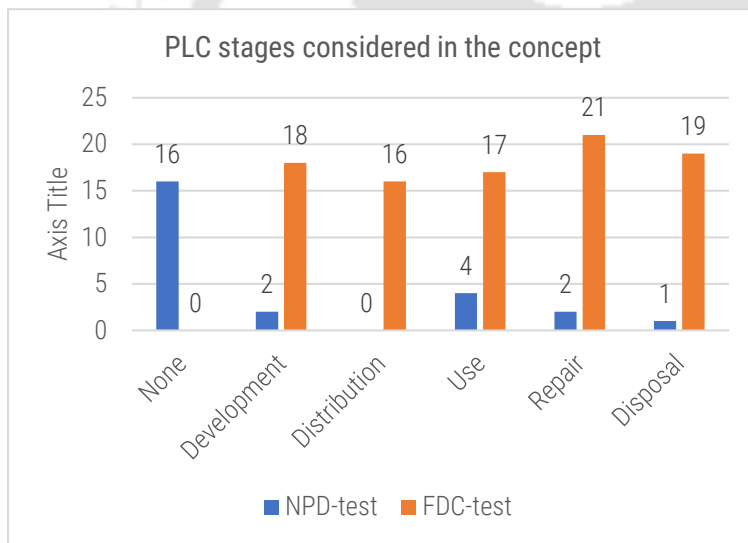


Figure 5.16: Number of final concepts from NPD and FDC-test with explicit information related to the PLC stages.

In a related analysis, concepts were also checked for the aspects of the product life cycle (PLC) stages considered in the final solution. This analysis was important since one of the goals of the FCD framework is to enable the designer in generating design holistic frugal concepts. Figure 5.16 shows that concepts generated using the FDC-test workbook considered the PLC stages to a larger extent. Interestingly, very few outcomes of the NPD-test explicitly reported information from the trailing stages of PLC. This result shows that the FDC-test workbooks better considered PLC stages in early design phases.

Similarly, an analysis was conducted using the CEH parameters. Figure 5.17 shows the number of final concepts from the NPD-test and FDC-test that recorded explicit information related to each of the CEH parameters. It can be seen that largely the FDC-test concepts contained more information related to the CEH parameters. This result could mean that the FDC framework better enabled subjects to consider the effect of the CEH parameters when developing the concepts.

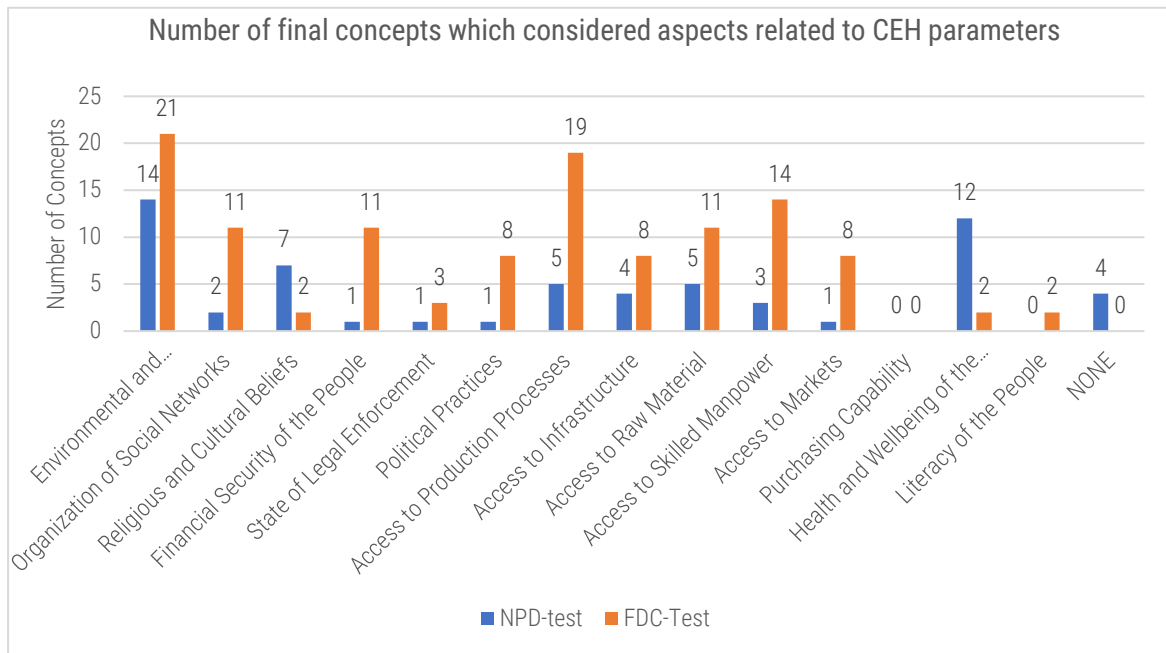


Figure 5.17: Number of final concepts from NPD and FDC-test with explicit information related to each CEH parameter.

Next, an analysis was performed to understand how the concepts considered various guidelines for frugal design. It was an interpretive exercise where concepts were checked, and details that seemed relevant to one or more design guidelines were noted. Figure 5.18 provides an indicative result showing how concepts considered some of the key frugal design guidelines.

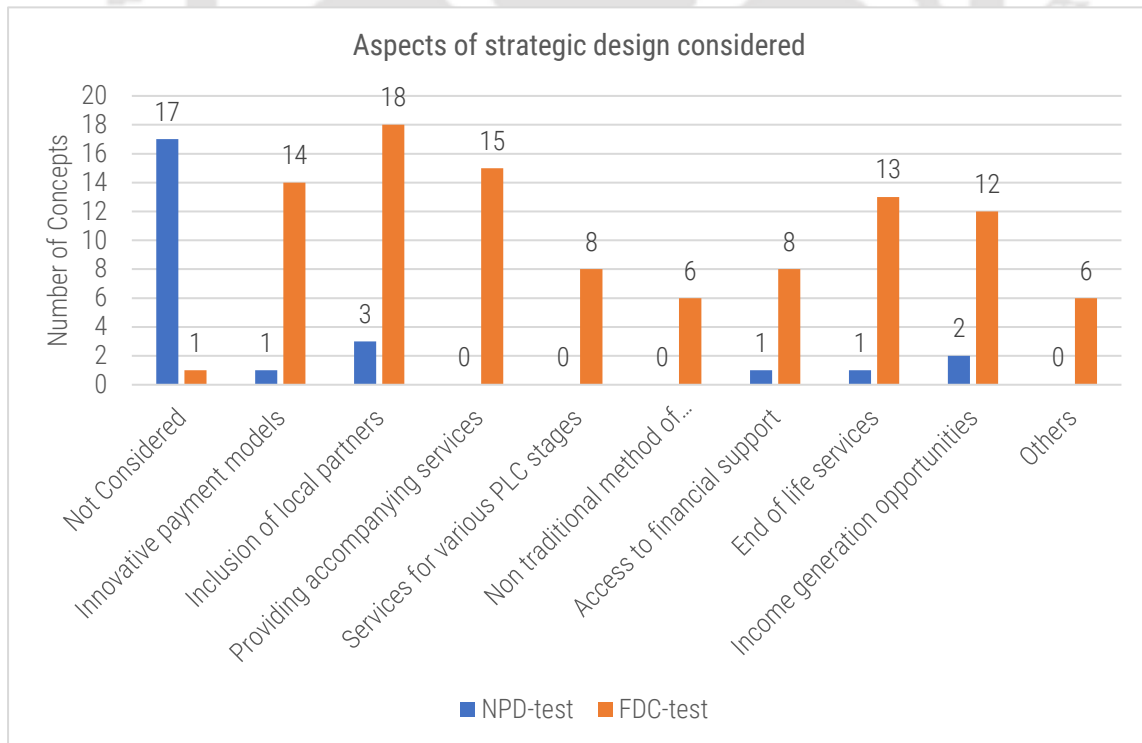


Figure 5.18: Number of final concepts from NPD and FDC-test with explicit information related to Strategic Design guidelines

Additionally, information about payment models and dissemination of the final concepts was assessed. It was assumed that designers had considered business design aspects if concepts contained information regarding appropriate payment models. Similarly, dissemination aspects were assessed since it is a key aspect of frugal design. Figure 5.19 and 5.20 shows the results of these assessments.

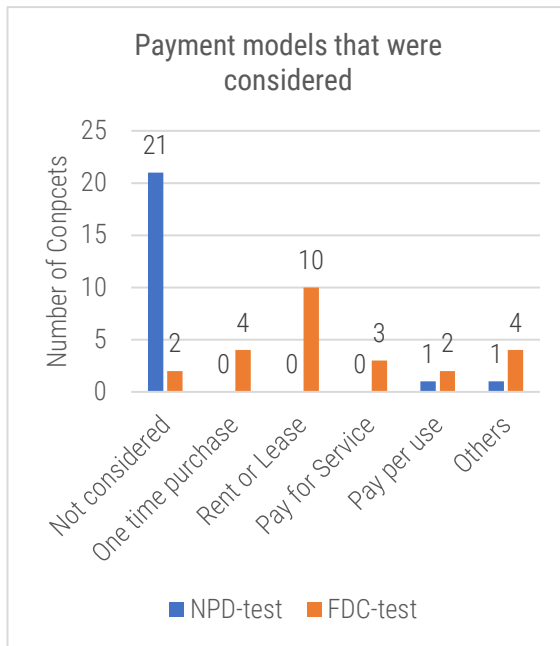


Figure 5.19: Number of final concepts from NPD and FDC-test with explicit information related to payment models.

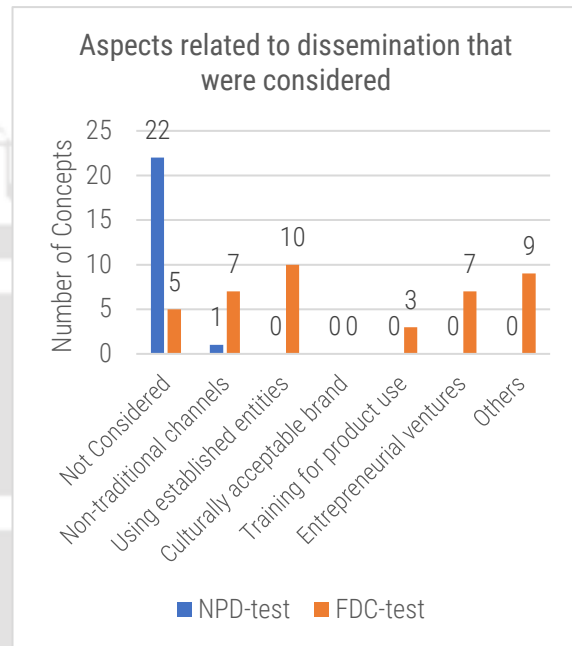


Figure 5.20: Number of final concepts from NPD and FDC-test with explicit information related to Dissemination.

There was a significant difference between NPD-test and FDC-test outcomes considering the strategic aspects of design. Nearly all of the NPD-test outcomes did not consider many strategic design guidelines. This outcome was obtained despite both the workbooks containing information on the strategic design aspects. Moreover, the importance of developing holistic concepts in MC was iterated in all the test briefing sessions. Also, the NPD-test concepts mostly did not consider the payment models and dissemination alternatives. This result shows that the FDC-test workbook enabled subjects to consider the strategic frugal design guidelines more effectively in their concept proposals.

Finally, to understand if the FDC-test and NPD-test outcomes were comparable considering product development details, it was assumed that a product was sufficiently detailed if it considered specific materials and the manufacturing processes. Figures 5.21 and 5.22 show the materials and manufacturing methods considered by subjects in their final solutions. It can be seen that in both test scenarios, subjects developed their solutions with enough details to think about the materials and the manufacturing processes. This analysis indicated that subjects could produce comparable details in product embodiment using both the NPD-test and FDC-test workbooks.

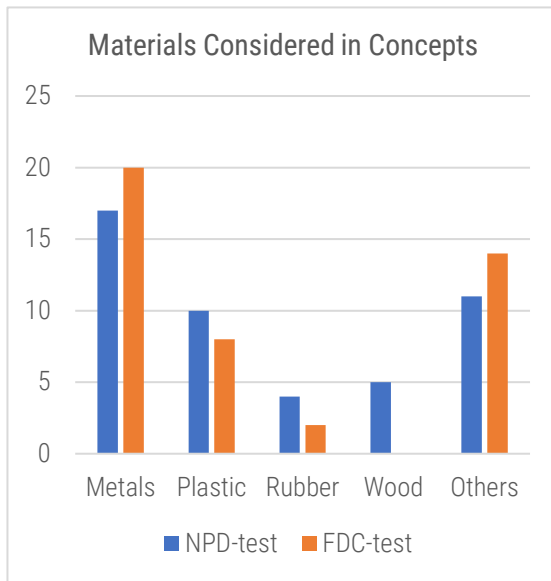


Figure 5.21: Type of Materials considered by the final concepts from NPD and FDC-test.

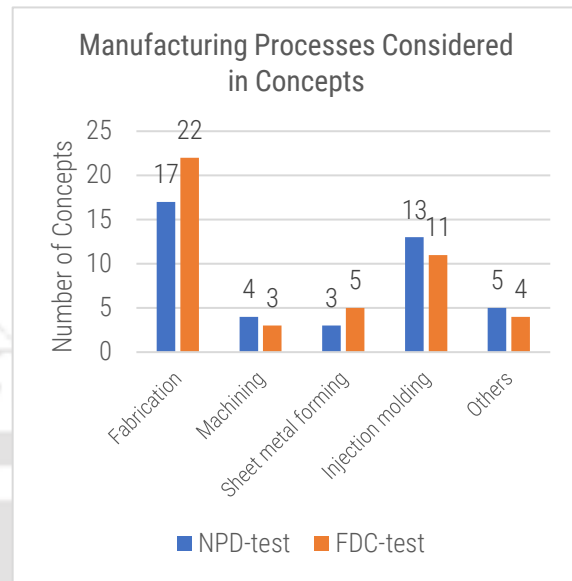


Figure 5.22: Type of manufacturing processes considered by the final concepts from NPD and FDC-test.

The qualitative analysis of DCE outcomes provides a glimpse of how the FDC framework enables designers in developing frugal and holistic solutions. The FDC-test workbook enabled better considerations of the myriad guidelines and best practices found in the literature. The qualitative analysis also indicated some shortcomings of the NPD process, especially its lack of supporting designers in creating holistic solutions. Also, when following the NPD-test workbooks, subjects did not incorporate many frugal design guidelines despite their explicit mention. Qualitatively speaking, the FDC framework was able to mitigate such issues. However, objective tests can only establish if following the FDC framework resulted in better design concepts.

5.4 Results of Experimental Study

The methodology section explained the study design and measurement method using MCDM methods. The MCDM methodology was then used to generate 'closeness coefficient' (CC_i) values, the cumulative scores obtained by the 46 concepts in expert evaluation (See Appendix H for calculations). Table 5.3 provides the closeness coefficient (CC_i) scores in percentage for each concept in the subjective evaluation by experts using FVDUS and CEH parameters.

Table 5.3: Closeness Coefficients (CCi) values (in %) obtained from Rough group, TOPSIS [34] evaluation of concepts, developed using NPD-test and FDC-test workbooks. Numbers in brackets near subject names are identifiers and have no statistical meaning.

Subject Name	NPD-Test CCi for FVDUS parameters	NPD-Test CCi for CEH parameters	FDC-Test CCi for FVDUS parameters	FDC-Test CCi for CEH parameters
Mehul (21)	48.15%	41.97%	55.61%	42.72%
Abhishek (02)	22.33%	17.51%	82.88%	53.19%
Mahendra (11)	15.65%	13.36%	57.99%	37.13%
Zankar (36)	52.66%	34.41%	64.50%	41.70%
Akhil (02)	10.80%	14.02%	78.38%	62.84%
Nilutpal (112)	40.40%	30.29%	57.73%	35.43%
Mukesh (24)	31.03%	21.67%	72.23%	57.03%
Manas (19)	4.93%	8.01%	60.65%	48.33%
Pradeep (42)	38.29%	27.20%	55.38%	41.95%
Suraj (23)	35.43%	17.75%	51.30%	47.26%
Raunak (32)	21.13%	18.81%	40.09%	51.25%
Sangram (22)	23.44%	20.48%	44.73%	37.21%
Kirankumar (15)	17.65%	12.38%	56.64%	36.72%
Kiran (05)	23.63%	13.49%	45.44%	38.33%
Dipankar (09)	18.41%	13.41%	58.94%	41.90%
Shubhangi (38)	23.52%	13.95%	66.52%	42.82%
Prashanth (29)	24.58%	18.34%	56.73%	43.84%
Shubhank (39)	39.25%	22.46%	68.04%	51.28%
Vaibhav (40)	10.10%	11.12%	32.56%	25.91%
Group1: Shubhank (39), Shubhangi (38), Manas (19), Sangram (22)	35.55%	16.63%	47.07%	36.36%
Group 2: Pradeep (42), Rounak (32), Vaibhav (40), Prasanth (29)	34.68%	16.61%	68.30%	41.40%
Group 3: Nilutpal (112), Kiran (05), Abhishek (02), Suraj (23)	46.61%	29.17%	56.05%	39.26%
Group 4: Zankar (36), Kirankumar (15), Dipankar (09), Mehul (21), Mukesh	26.82%	21.12%	70.33%	51.39%

(24), Mahendra (11)				
Mean	28.04%	19.75%	58.61%	43.71%
Standard Deviation	12.73%	8.15%	12.05%	8.20%

It can be seen that the standard deviation of the CCI values is similar. Also, the FDC-test means are much higher than NPD-test, which is an initial indication that experts evaluated the FDC-test results more favourably using both FVDUS and CEH parameters. Looking at only the FVDUS CCI values where subjects worked individually, the mean is 26.4% (sd=13.05%) and 58.23% (sd = 12.52%) for NPD-test and FDC-test, respectively. Similarly, the mean of CEH CCI scores with individual subjects is 19.51% (sd = 8.66%) and 44.04% (sd = 8.63%) for NPD and FDC-test respectively (n=19). Figure 2.23 shows the results graphically. The CCI scores shown above are used for conducting the relevant statistical tests discussed below.

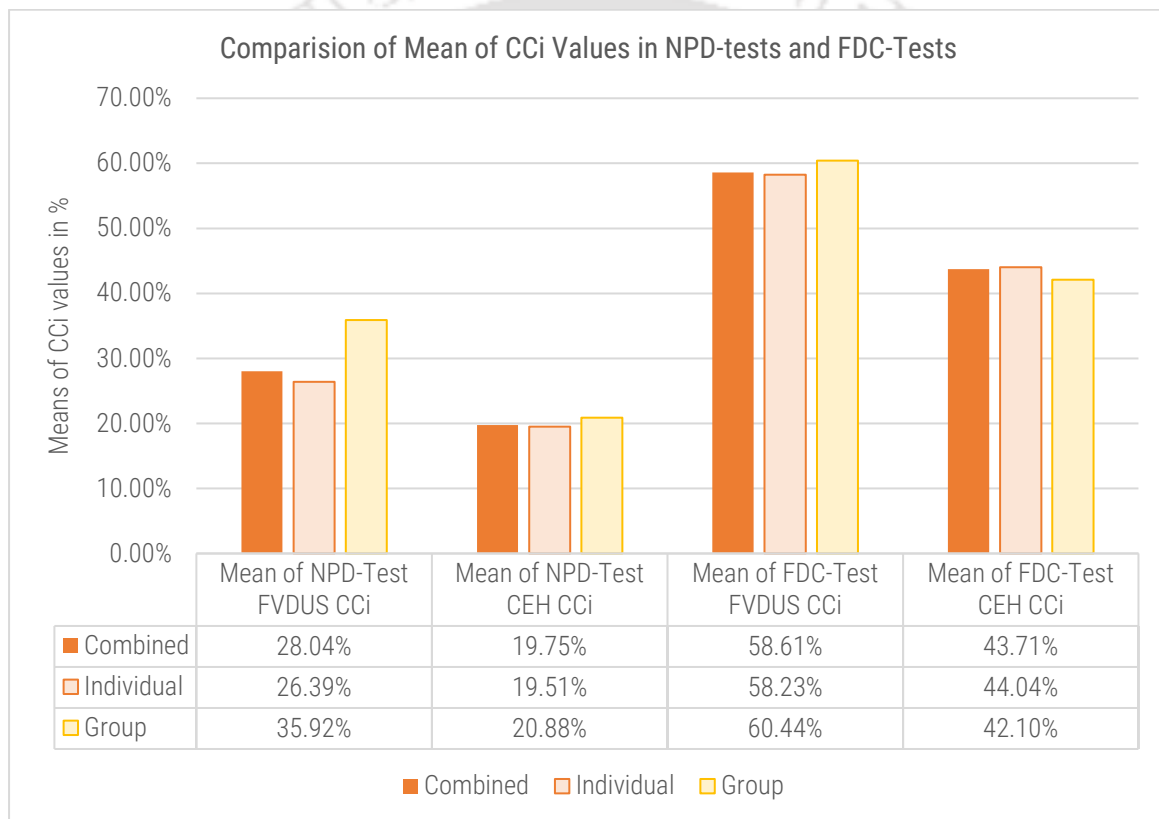


Figure 5.23: Closeness Coefficient (CCI) Scores obtained by concepts in NPD-test and FDC-test.

Statistical methods for dependent groups can be considered for hypothesis tests since the concepts were generated by the same subject (group) in both tests. For dependent samples whose measures have to be compared, the characteristic of one group determines that of the other. In dependent samples, it is assumed that subjects who score low in the before-tests are more likely to score low in the after-tests as well.

The Student's τ test for paired comparison of dependent measures was chosen to compare the outcomes from the NPD-test and FDC-test. The Student's τ test will use the standard deviation of the difference between the CCI Scores obtained using the NPD-test and FDC-test workbooks. The test is suitable for use when samples are below 30. However, a significantly smaller sample size

reduces the accuracy of the statistical inferences. Since the sample contains 19 (+4 group) subjects, a much higher τ value will be needed to reject the null hypothesis for a significance of 0.05 than if the sample was, say, greater than 30.

Furthermore, for administering the τ test, the variable must be normally distributed and an interval measure. The CCI value is a relative measure of the distance between an actual concept and the theoretical best and worst concepts. The theoretical best concept can take the CCI value one (i.e. 100%), and the theoretical worst can take zero. All other concepts which are evaluated would lie in between the value of zero and one; therefore, the CCI value is an interval scale. Additionally, CCI scores will normally be distributed if the population is sufficiently large and a large number of experts evaluate the solutions. Therefore, CCI values will be normally distributed in the population of novice designers.

Figures 5.24 & 5.25 shows the distribution of difference of CCI values graphically. The difference in CEH CCI values is fairly well distributed considering the relatively small sample size (skewness = -0.14, kurtosis = -0.03). The distribution of difference of FVDUS CCI scores is within acceptable limits for a paired τ test as well (Skewness = 0.57, kurtosis = -0.48). However, a paired sample Wilcoxon signed-rank test is also conducted with the FVDUS CCI scores to ensure robust results in the hypothesis test.

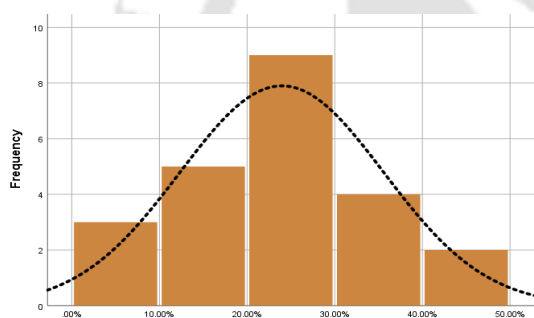


Figure 5.24: Distribution of difference in NPD-test and FDC-test CCI Scores using CEH parameters.

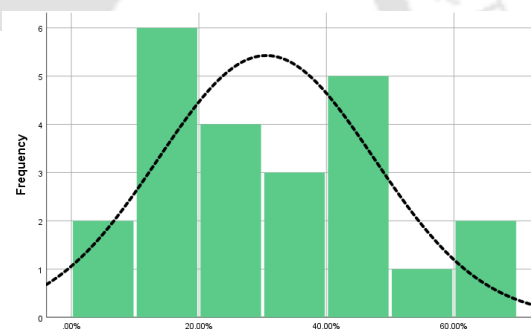


Figure 5.25: Distribution of difference in NPD-test and FDC-test CCI Scores using FVDUS parameters.

The hypothesis formulated intended to test if experts perceived the FDC framework concepts better than those generated using a typical product design process. The null hypothesis can be interpreted as 'the mean of difference of CCI scores of concepts from both the test will be zero for the population'. The directional hypothesis is that the mean of 'difference of CCI scores of concepts' will be greater than zero. The following table summarises the outcomes of the paired sample Student's τ test.

Table 5.4: Results of dependent sample Student's τ test.

Variable Pair	Mean of difference	Std. Dev of difference	Calculated Student's τ	τ value for $\alpha = 0.05$ (2 tailed)	τ value for $\alpha = 0.01$ (2 tailed)
FDC-Test CCI using CEH - NPD-Test CCI using CEH	23.96%	11.62%	9.89	2.074	1.171
FDC-Test CCI using FVDUS - NPD-Test CCI using FVDUS	30.57%	16.91%	8.67	2.074	1.171

As it can be seen that in both the paired comparisons, the calculated Student's τ value is greater than the critical τ values at a significance level of 0.05 and 0.01 (i.e., $9.89 > 2.074 > 1.171$ and $8.67 > 2.074 > 1.171$). Thus, there is sufficient evidence to reject the null hypothesis.

Therefore, there is significant evidence that Concepts designed using the FDC framework are perceived to be better than concepts designed using a general design approach by experts when evaluating using subjective parameters.

Additionally, a paired sample Wilcoxon signed-rank test was conducted specifically for the CC_{iFVDUS} values since its distribution could make the Student's τ difficult to interpret. Using just the CC_{iFVDUS} values in the Wilcoxon signed-rank test also resulted in a rejection of the null hypothesis.

Furthermore, the study design allows for conducting a repeated-measures ANOVA [49], [50]. However, the statistical methods have not been used for hypothesis testing due to concerns regarding the effect of smaller sample sizes and (in the case of CC_{iFVDUS} values) normality. Nonetheless, the test provides added understanding of the data.

The results of a repeated-measures ANOVA using the CC_{iCEH} scores indicated a significant effect of the FDC-workbook on the design concepts with **Wilks' Lambda = 0.184, F (1, 22) = 97.81, p < 0.1, partial $\eta^2 = 0.82$** . The results of a repeated-measures ANOVA using the CC_{iFVDUS} scores indicated similar results with **Wilks' Lambda = 0.226, F (1, 22) = 75.16, p < 0.1, partial $\eta^2 = 0.77$** . Therefore, if the results of repeated-measures ANOVA are considered, the null hypothesis can be safely rejected as well.

5.4.1 Correlation between CEH and FVDUS parameters

A subsequent test of interest was related to CEH parameters as an alternative means of concept evaluation. The underlying question was if design concepts could be evaluated using CEH parameters at the early stages of design and if such an evaluation would align with the expert perception. Therefore, it would be interesting to know if subjective evaluation using CEH parameters correlated with the subjective evaluation using FVDUS parameters. Based on literature review [5]–[7], designers and experts typically use the FVDUS parameters for concept evaluation. A correlation would mean the CEH parameters can be used similarly to FVDUS parameters to evaluate concepts during early design phases.

A sample containing all the concepts generated from the NPD-test and FDC-test is considered to understand the correlation. Although this is not a random sample since at least two concepts were created by a single subject, since the regression of the values is not of concern, the product-moment correlation using Pearson's r is a meaningful metric. Moreover, since the CC_i values are continuous, Pearson's r can be considered for this purpose.

Figure 5.26 shows the scatter diagram of the CC_i values obtained using FVDUS and CEH parameters in expert evaluation. Each dot represents a concept where the x-axis shows its CC_i scores using FVDUS parameters and the y-axis shows its CC_i scores using CEH parameters.

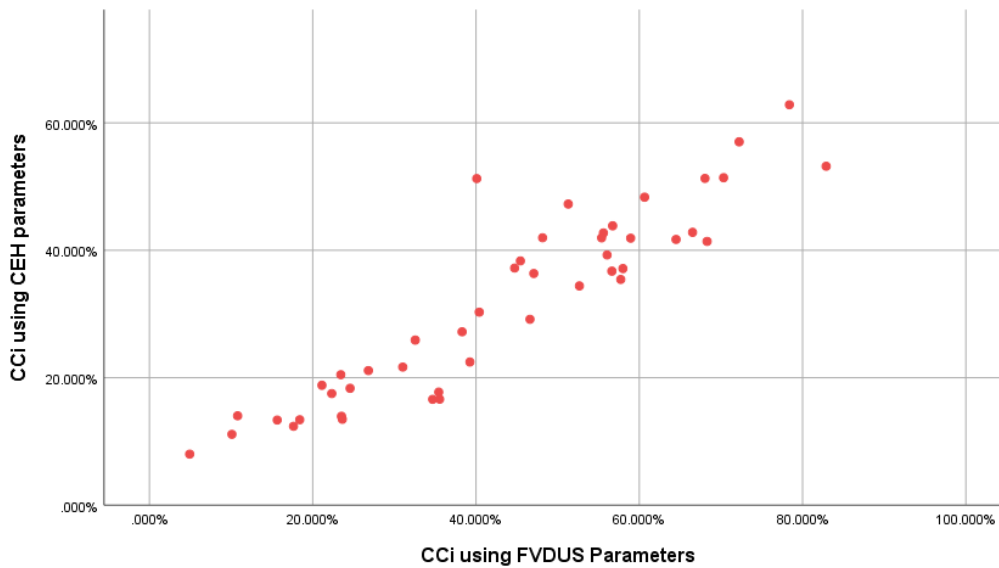


Figure 5.26: Simple scatter plot of CCI values obtained using CEH parameters and FVDUS parameters.

A Pearson’s r-value of 0.91 was calculated for the CCI values obtained using CEH and FVDUS, which shows a significant correlation between the two values. As a thumb rule, Pearson’s r value between 0.75 and 1 is considered a very high association [51, p. 272].

Table 5.5: Pearson’s r value showing a correlation between CEH CCI Scores and FVDUS CCI Scores at different levels of expert optimism.

Expert optimism in evaluation	Pearson’s r correlation
10%	0.950
26%	0.954
42%	0.955
58%	0.953
74%	0.946
90%	0.933

The correlation was assessed considering the change if experts were either not confident or very confident in their subjective evaluations to further understand the relation between the values. The rough TOPSIS method utilised uses a ‘confidence in evaluation’ (α value, see Appendix H) for obtaining the CCI values.

The CCI values using CEH and FVDUS parameters were calculated using a range of α values (0.1, 0.26, 0.42, 0.58, 0.74, 0.9) to represent the possible variation in expert optimism during evaluation. Pearson’s r-value was calculated for CCI values at each optimism level to check if the correlation changed with ‘changes’ in experts’ optimism during concept evaluation. The table shows that the CCI values are highly correlated even when there is a considerable difference in experts’ confidence in their subjective evaluations.

The high correlation means that expert evaluation using CEH parameters is similar to expert evaluation using FVDUS parameters. Consequently, CEH parameters can be used instead of the FVDUS parameters for concept evaluation, especially in design for MCs. Knowing this, designers can design frugal solutions considering the various CEH parameters and be certain that the solutions would improve on FVDUS parameters.

5.5 Discussion

The Chapter presented an empirical evaluation of the effectiveness of the FDC framework. The experiment aimed to understand if concepts generated following the FDC framework were better than those generated using a typical design approach. Nineteen subjects generated solutions through a series of design conceptualisation exercises (DCE) for design problems in a selected marginal context. Five experts then evaluated the concepts to understand if those generated using the FDC framework were better. It was assumed that consistently better concepts indicate that the FDC framework was an effective approach for designing solutions for marginal contexts.

The DCE exercise produced fruitful results in the experiment. Qualitative assessment of the outcomes suggested that subjects could utilise a (relatively) short duration to generate meaningful frugal solutions for evaluation. Still, the DCEs presented only a longitudinal view of implementing the FDC framework. Some other aspects of the framework, such as participatory research and development activities, could not be entirely tested. Nonetheless, it can safely be assumed that participatory activities would only enhance the effects given the positive results.

The concepts in the experimental DCE sessions (FDC-tests) were also found to be holistic. This result can largely be attributed to the workbooks that implemented the FDC framework. The operationalisation of the FDC framework was done using a design workbook. Design workbooks are argued as an effective means of practically implementing design theories [12]–[14]. The FDC-test workbook effectively operationalised the FDC framework and implemented it in the DCE sessions. The pilot tests and study outcomes indicated that the workbooks could systematically and effectively guide subjects through the FDC framework.

Designing the workbook provided an opportunity to envision design supports based on the FDC framework. It is entirely possible to elaborate the FDC-test workbook into a full-fledged design tool to support the design of holistic and frugal product solutions for MC.

It was important to provide a design context and briefs for the DCE exercises and the expert evaluation. Design briefs extracted from the project related to the washermen community were used for the purpose. The project provided a marginal context for designing concepts and various aspects of the CEH framework, forming a basis for concept generation and evaluation. The DCE outcomes can be considered independent of the MC selected because the overall scores obtained by the solution were independent of the specific MC, i.e. had a different context been selected, the outcomes would have been similar. Therefore, the FDC framework and the workbook can be used effectively in other contexts as well.

A total of 46 design concepts were generated in four DCE sessions, of which 38 were generated individually by subjects and eight were generated by subjects working in groups. These 46 design concepts formed the basis of the assessments. A qualitative evaluation of the design concepts was conducted to understand how well the solutions met some of the key objectives of the FDC framework.

Firstly, subjects generated a markedly larger number of ideas when using the FDC-test workbook in groups. Moreover, the number of ideas generated by subjects individually using both the workbooks were similar. Additionally, subjects generated a similar number of ideas when working individually using the NPD-test workbooks.

It could be that the FDC-test workbook enables better group ideation and hence could mean that the framework enabled collaborative ideation. However, the difference could also be attributed to other reasons. For example, it could be that the subjects became more comfortable working with each other since the FDC-test was conducted towards the latter half of the course timeline. Therefore, the effect of the FDC framework for participatory work needs to be tested separately.

Other qualitative checks were conducted to see how well the concepts met the frugal design guidelines and if they presented details related to the FVDUS and CEH parameters. It was observed that information related to FVDUS parameters was mentioned by all concepts nearly uniformly. However, the concepts generated in FDC-test were the ones that consistently considered the various CEH parameters in their description despite these parameters not being specifically mentioned in the workbook. The concepts generated using the FDC-test workbook also incorporated ideas related to most product lifecycle stages. The analysis showed that the FDC-test workbook was relatively effective in making the subjects consider the constraints in MC and integrate strategic measures into the solution.

Furthermore, the FDC workbook seems to promote more holistic thinking during concept generation since the subjects considered aspects of CEH and the FVDUS parameters. Therefore, the FDC framework could be beneficial for developing holistic solutions for marginal contexts.

A set of selected frugal design guidelines for strategic design and dissemination were used to check if the concepts considered them in the final proposal. Although concepts in both the NPD-test and FDC-test were equally considerate of product embodiment requirements (checked by finding manufacturing and materials details provided), the concepts from the FDC-test considered the strategic design guidelines in more detail. Incidentally, these design guidelines were described to the subjects before all four DCE sessions. The NPD-test workbook also listed these guidelines on the first page for ease of recall. The outcome shows that the FDC-test workbook enabled the designers to incorporate the various guidelines effectively.

The hypothesis tests were conducted after the detailed qualitative evaluation. Paired dependent samples Student's τ test, Wilcoxon's signed-rank test and a repeated-measures ANOVA were conducted. The Student's τ test and Wilcoxon's signed-rank test were used for testing the hypothesis.

The 46 concepts generated in DCE represented 23 pairs of concepts, one generated using the NPD-test workbook and one with the FDC-test workbook. All 46 concepts were evaluated by five experts separately. The evaluation followed an AHP and TOPSIS methodology selected for the study. The evaluation outcome was a single value for each concept called the Closeness Coefficient (CC_i), which was considered the score obtained by the concept in the evaluation. These CC_i values were used for the statistical tests. Two different CC_i values were obtained, the CC_{iCEH} value and the CC_{iFVDUS} value based on the CEH and FVDUS parameters used in the evaluation.

Normality tests on the difference of CC_i scores from the NPD and FDC tests were performed to see if they could be used in a Student's τ test. The difference of CC_{iCEH} values from NPD and FDC-tests was close to a normal distribution. The difference of CC_{iFVDUS} values from NPD and FDC-tests were slightly skewed but within acceptable limits. For robust results, a Wilcoxon signed-rank test was done for the CC_{iFVDUS} values.

The null hypothesis, H_0 , was tested, which said there is no difference in mean CC_i values between the concepts generated using NPD-test workbooks and those generated from FDC-test workbooks.

The null hypothesis was rejected with a significance value of $\alpha = 0.1$ and $\tau = 9.89$ for CC_{iCEH} . For CC_{iFVDUS} values, H_0 was rejected at $\alpha = 0.1$, with a $\tau = 8.67$. Thus, the concepts generated using the FDC-test workbook fared significantly better than those generated using the NPD-test workbook in a subjective evaluation by experts using FVDUS and CEH parameters.

The hypothesis test provides evidence that the FDC framework enabled better concepts of frugal solutions for marginal context. Moreover, concepts generated were also more holistic since their mean CC_{iCEH} Scores were higher when using the FDC-test workbook. Furthermore, the FDC-test workbook proved to be an effective way of practically implementing the FDC framework. Not only was the workbook able to help designers systematically execute the FDC framework, but it also provided an effective means of implementing various frugal design guidelines. Therefore, an elaborate version of the FDC-test workbook can be used by designers as a tool.

Another test of interest in the study was the correlation between CEH and FVDUS parameters. CEH parameters represent the typical constraints that affect solutions' design, development, and dissemination. It was argued that solutions that can successfully mitigate CEH constraints while adequately fulfilling the design brief can be considered good concepts.

It was also hypothesized that design concepts could be evaluated using CEH parameters at the early stages of design and that such an evaluation would align with the expert perception. The test was conducted by looking at the correlation between the expert evaluation of concepts using CEH and FVDUS parameters. It was assumed that FVDUS parameters represent the expert perception about design concepts, i.e. concepts which score high in FVDUS parameters are considered better by the experts. The Pearson's r correlation was tested between CC_{iCEH} and CC_{iFVDUS} values, and a high correlation was observed.

Additionally, the change in correlation based on the variation of optimism in the subjective evolution of experts was assessed. In all cases, a high Pearson's r value indicated a high correlation between the CC_{iCEH} and CC_{iFVDUS} values. This result shows that the experts evaluated the concepts similarly when considering the more contextual CEH parameters and the more generic FVDUS parameters.

The correlation between CC_{iCEH} and CC_{iFVDUS} values suggest CEH parameters can be used for subjective evaluation of design concepts for marginal context as efficiently as the FVDUS parameters. The FVDUS parameters are typically a more generic way of subjectively evaluating a concept in the early stages of development. In contrast, the CEH parameters are unique to the marginal context and provide a more elaborate scope for evaluation. For example, there are 14 parameters in CEH which focus on different aspects of the context, thus providing a more granular way of analysing design concepts.

Moreover, knowing that a concept which fairs well in the CEH parameter is also likely to be better in FVDUS parameters means that designers can use the CEH parameter to direct their concept generation efforts. The CEH parameters can thus be used to highlight specific aspects of the marginal context and focus research efforts to understand it better. Designers can also use the CEH parameters as a guide or a checklist to review the designed concepts and improve them during the early design stages. Since CEH parameters are more elaborate than the conceptually broader FVDUS parameters, they are easier to implement as a tool for directing concept generation. Therefore, the CEH framework can effectively direct a frugal design process and evaluate solutions at early design phases.

The study presented here helped meet some of the key research lacunae identified in the thesis. The FDC and CEH frameworks seem effective for systematically generating holistic and frugal product design solutions for marginal contexts. The design of the FDC-test workbook provides a clear direction for developing practical design supports which operationalise the frameworks and various frugal design guidelines.

5.6 Conclusion

The Chapter presented an empirical evaluation of the FDC and CEH framework synthesised as part of the thesis. The empirical evaluation was done through a concept generation exercise. In the exercise, subjects generated concepts using an implementation of the FDC framework, which were compared to concepts generated using a typical design approach. An experiment with a repeated measures study design was found suitable for the purpose. The work presented here can be considered a quasi-experimental study since the sample selection was not entirely random. However, the study can safely infer several insights regarding the frameworks and the frugal design approach.

The ideal way for evaluating the FDC framework would have been through repeated implementation in live design projects. However, such an implementation needs long term engagement and extensive resources, which made it out of the scope of this research. In comparison to a live project, a DCE is conducted in shorter durations and within controlled, and in many cases, contrived settings. The process can only be understood as a simulation of an actual concept generation process. Therefore, it cannot completely illustrate the benefits of using the framework in a real-life project where designers have access to more resources, time, and a first-hand understanding of the design opportunities. However, on the positive side, the controlled nature of a DCE enables the researcher to isolate and study its effects properly.

A less resource-intensive way for evaluation could be through a series of design workshops and qualitative evaluation of outcomes. However, it can be argued that such a method is difficult to replicate and provides more anecdotal evidence. Still, an effective triangulation can be done by conducting such studies. Such qualitative studies can be considered future work of this thesis.

Several steps in the experiment were considered to improve the overall internal validity and reduce biases. However, there are some overall limitations to the study. Firstly, the concept generation exercises provided only a longitudinal view of implementing the FDC framework in a live design project. The workbooks had to be designed to capture sufficient details, still not be overwhelming in a three-hour exercise. Thus, there were restrictions on the conceptual details that subjects could develop. A longer duration could have produced better results. Also, a methodological limitation of repeated measures study design is the effect of one test on another. Although several measures were taken to minimise such effects, some other inadvertent noise may still affect the study results. Therefore, the results have to be interpreted with such considerations.

Second, the raw data generated in the exercise could not be given to the experts for evaluation directly (it spanned over 600 pages). Therefore, a two-page summary of the design concepts was made. Although a uniform quality was maintained, some information could have been omitted or lost to translation.

Third, the chosen empirical method only tested the 'perception' of the expert when they evaluated the concepts subjectively. Whether the concepts generated using the FDC framework and FDC-test workbooks are better can only be said with full-scale prototypes and performance tests. Such activities, unfortunately, were implausible for 46 concepts and out of scope for the thesis work.

Finally, The Design activities and the FDC-test workbook represent only one way of operationalising the FDC framework. There could be other ways to do so. The effectiveness of the FDC framework can be extrapolated from the experiment since the FDC-test workbook was carefully created from a set of Design Activities presented in Chapter 4. However, a radically different version of the FDC-test workbook could also be created. Such an implementation would produce similar results only if the objectives of the FDC framework phases are effectively met.

The study presented here can be considered a first attempt at empirically evaluating the frameworks. A randomised controlled experimental study with design practitioners will provide the most generalizable insights on the effectiveness. Such study can be considered future work in the thesis.

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Chapter 6 Strategies for A Frugal Mindset

This thesis has presented several insights related to frugal design for marginal contexts (MC). Most of the discussion has focused on a systematic process and its execution. Like most design theories found in literature, our discussions have also been agnostic of the designer. Design theories typically assume a common denominator when considering the skill needed in execution. In most cases, understanding a designer's skill level is adequate in implementing design theories in practice. However, we found that implementing a frugal design process also depends on a unique 'mindset' and goes beyond just the considerations of the designer's skill level. Therefore, understanding the 'frugal mindset' is crucial for implementing a systematic design process and creating frugal solutions.

According to the literature, novice and experienced designers differ beyond their skill level when designing in MC. Novice designers find it challenging to design solutions for MC, and their thought processes are significantly affected by their backgrounds [1]. On the other hand, many authors suggest that experts showcase a unique 'mindset' that helps them execute a design process efficiently while having limited access to resources [2], [3]. This 'mindset' that enables the effective implementation of a design process in MC and efficient design of solutions within resource constraints can be called a 'frugal mindset'. Although a systematic process can partially help develop such a mindset, clearly, some aspects of it lie outside of a design process and are characteristics that a designer must imbibe.

Still, the 'frugal mindset' phenomenon remains unexplored in literature. This chapter presents an exploratory study to understand the phenomenon. The outcomes are appended to the frugal design frameworks synthesised earlier.

6.1 Introduction and Background

The objective of our study was to understand 'Frugal Mindset' in the design context and identify strategies for implementing or imbibing it in practice. The literature review presented in Chapter 1 found that a frugal mindset is an important component in effectively implementing approaches and tools for frugal design in marginal contexts (MC). However, the understanding of the phenomenon, especially from a design point of view, is unclear.

Several research publications have indicated the idea of a 'mindset' as an essential component of the design process related to marginal contexts. Baker and Nelson speak about a 'bricolage attitude' when discussing how organisations can innovate in resource-poor environments [4]. They suggest that the mindset is rooted in an attitude of parsimony towards resource utilisation when developing specific solutions. Similarly, Radjou et al. [5] discuss the idea of a 'Jugaad mindset' in their popular book '*Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough Growth*'. They suggest that the mindset is characterised by resilience, flexibility and frugality. In another book,

'Frugal Innovation: How to do better with less' [6], Radjou and Prabhu indicate the idea of a 'frugal and flexible mindset' and discuss how individuals in organisations can imbibe its characteristics to create frugal innovations. However, in none of these sources, the phenomenon is ever concretely defined to allow scientific scrutiny, despite strongly suggesting that the design process is dependent on it.

The term 'frugal mindset' has gained some meaning in recent literature, where authors have attempted to clarify its definition in certain contexts. An initial attempt was by Soni et al. [2]. In their characterisation and attempt at defining 'frugal innovation', they suggest that a 'frugal mindset' is an essential component along with a 'frugal outcome' and a 'frugal process'. The three aspects are combined to form a 'frugal innovation'. They suggest that a frugal mindset is a "way of life" defined by prudence in financial management, improvisation, adaptation to resource scarcity and tolerance for uncertainty. Still, a clear definition is not provided.

Two recent publications have provided the most clarity on the phenomenon, albeit in a strictly contextualised setting. Krohn and Herstatt [7] take a stand on defining the frugal mindset using a theory of 'global mindset' based on a systematic literature review. They suggest that it is a cognitive orientation towards improving task performance leading to a better understanding of consumers, satisfaction of their needs and overall strategic alignment of the solution. Their strategy for implementing a frugal mindset is by accepting new realities, reconsidering current approaches and implementing adapted ones. However, their discussion is focused on the 'frugal mindset' of individual decision-makers within an organisational context and is not necessarily relevant for designers creating frugal solutions for MC. In related work, Krohn et al. [8] further elaborate frugal mindset and frame it with Gollwitzer's theory of action phases [9]. However, the work remains centric on managerial decision making in an organisational context. Nonetheless, Krohn and colleagues [7], [8] work provides the contemporary understanding of the frugal mindset phenomenon. Relevant insights from their work can be summarised as follows:

Although the presented literature provides a glimpse into the 'frugal mindset' phenomenon, it is difficult to adapt it into design theory. Not all insights are relevant to design practice and execution of a frugal design process. Moreover, the insights cannot be effectively operationalised into supports for design practitioners. Therefore, a deeper dive into the phenomenon, specifically from a design perspective, is important.

6.1.1 What is a Mindset?

The construct of 'mindset' has been substantially explored in cognitive psychology. A mindset can be described as "*the sum total of activated cognitive procedures in response to a given task*" [10]. Generally, mindsets are understood as cognitive operations and procedures which facilitate certain tasks and dictate how people interpret information [10]. Thus, 'task' and 'information handling behaviour' are central to conceptualising mindsets. Such a formulation has allowed for a large body of empirical studies that have helped understand the 'mindset' phenomenon in the cognitive psychology field.

Other formulations of 'mindset' exist in the literature related to business strategy and organisational leadership. In this field, the construct is understood as "*cognitive filters that attend to and influence the totality of cognitive processes with or without an identifiable task*" [10].

Mindsets are thus understood as a pattern of thinking in this conceptualisation. An example of this is the concept of ‘Local and Global mindsets’ [11]. These mindsets are understood as a cumulation of an ideal set of competencies, thought processes and attitudes that leaders need to support local or globally oriented organisations. The formulation has been criticised by French II [10] and Clapp-Smith & Lester [11] for its difficulty in allowing empirical validation.

Other conceptions of mindset exist in positive psychology and have been contested due to its underdeveloped nature [10]. Of the more famous conceptions of mindset, the idea of ‘Growth and Fixed Mindset’ have found significant attention [12]. In this formulation, mindsets are understood as common beliefs about human attributes.

In this research, the theories in cognitive psychology are consulted to develop a better understanding of the frugal mindset phenomenon due to its maturity. Gollwitzer provides the prevalent and formative theories in cognitive psychology to understanding mindset in the form of ‘Mindset theory of Action phases’ (MAP) and ‘Rubicon Model of Action Phases’ [10], [13]. Here, mindsets are exclusively associated with tasks performed by individuals and their goals and motivation to complete the task successfully. Mindsets are thus characteristics that affect how individuals handle information in a goal-oriented behaviour and dictate their motivations [9].

Gollwitzer Rubicon model of Action phases [9] theory divides the goal-oriented behaviour of individuals into four phases. These are the ‘Pre-decisional’ phase, ‘Decisional’ phase, ‘Actional’ phase and ‘Evaluative’ phase. Figure 6.1 shows the graphical representation of the Rubicon model presented by Gollwitzer [9]. The theory suggests that individuals display certain information handling behaviours within each ‘action phase’ called ‘mindsets’. The sum total of these behaviours can be called the overall mindset of the individual who pursues a goal. An individual’s motivations play an important part as it accounts for the effort exerted toward goal pursuit and the quality of the performance.

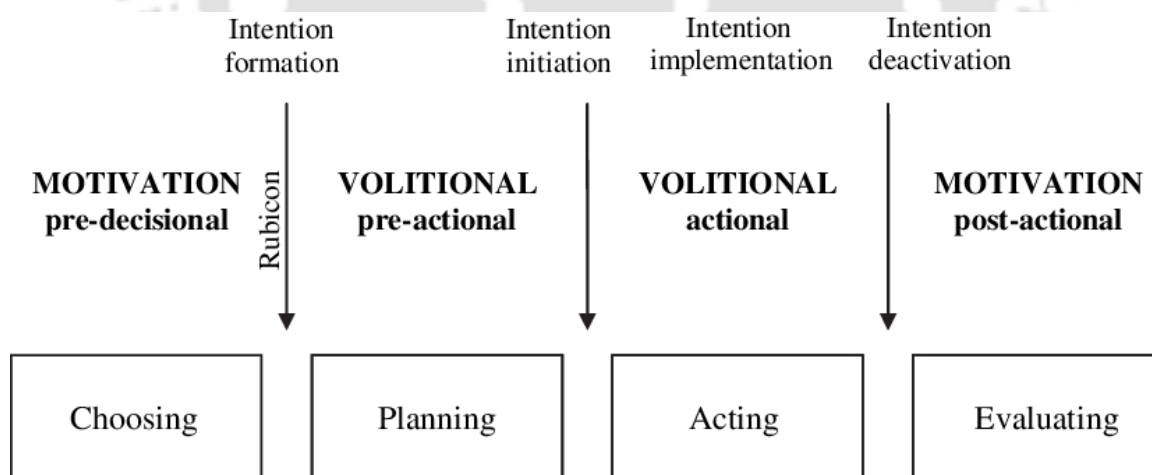


Figure 6.1: Gollwitzer’s Rubicon Model of Action Phases in Goal-oriented behaviour [9].

The Rubicon model has surprising alignment with the design process. The alignment can be understood by considering the task as ‘designing a solution’ and the goal as ‘creating a solution that meets users need satisfactorily’. Table 6.1 presents a brief description of the action phases, the mindsets associated with each phase and its alignment with the design process. This table also serves as a framework for understanding the ‘frugal mindset’ phenomenon.

Table 6.1: The Rubicon model of action phases [9] and its alignment with the design process.

Description of Action Phase	Associated Mindset	Alignment with the Design process
<p>Pre-Decisional phase: The individual is not yet decided on the goal or task to perform. Here, wishes are made which, when chosen after deliberations, become goals for the individuals. The motivation of individuals produces and inclines them towards the wishes they want to pursue. These wishes are then assessed for feasibility and desirability and compared to other competing wishes. The pre-decisional phase transitions to the next phase when individuals form a 'goal intention' to fulfil a deliberated wish.</p>	<p>A 'deliberative mindset' is associated with this phase. Such a mindset is characterised by open-mindedness or high receptiveness towards all types of information. There is a cognitive tuning towards information that enables assessing the feasibility and desirability of a particular wish. Additionally, there is an unbiased and impartial approach towards processing all acquired information.</p>	<p>A designer displays a deliberative mindset by an unbiased gathering and accepting novel information to evaluate design opportunities. With a deliberative mindset, the designer forms goal intentions and identifies the design directions that are feasible and desirable. In such a context, when one or more design directions are chosen for further work, it can be said that the designer has formulated some goal intentions. We can summarise the deliberative mindset of the designer by saying that s/he is looking for opportunities.</p>
<p>Decisional Phase: This is where individuals evaluate the information at hand and decide on actions that may lead to goal fulfilment. Before beginning, the individual has chosen a wish with high desirability and feasibility. Then a resolution or determination to pursue the wish is formed, at which point the individual has 'acquired a goal intention'. Formation of the goal intention marks the transition to the decisional phase. In this phase, individuals address "how, when, where" to act and make plans for initiating, executing or terminating the planned actions.</p>	<p>The mindset associated with this phase is the 'implemental mindset', where the individual is concerned only with specific information that answers questions of "how, when, where" to act. Individuals at this phase do not question the desirability or feasibility of the goal. They are attuned to relevant information and concentrate on promoting a chosen goal. Individuals tend to be closed-minded towards novel information to concentrate on their current situation and make a decision. There is a general optimism towards the information at hand being able to help with the goal.</p>	<p>Designers implemental mindset is associated with project planning and synthesis of research to develop ideas. In such activities, the designer is attuned to existing information or selectively seeks relevant information for creating new ideas and planning the project activities. There is an overall optimistic outlook towards the information being sufficient to solve the design problem. The designer is close-minded towards accepting new information and concentrates only on the information that forwards project planning or ideation. The implemental mindset can be summarised by saying that designers are 'Synthesising the research.'</p>

<p>Actional Phase: This is where individuals are focused on implementing the goal through planned actions. They act towards the goal to achieve what they had wished when setting their goals. Certain behavioural intentions determine the commitment to implementing a goal. The commitment (volitional strength) to the goal and favourability of the situation determine if any actions are initiated. Once the intention for initiation is present, the actional phase can start. The individual implements or executes the plans developed in the Decisional phase in this actional phase.</p>	<p>An Actional mindset is associated with this particular phase. The driving motivation in this mindset is to avoid or impede any disruption which can create divergence from established plans. Individual capabilities, alternative strategies, and the quality of the goal are ignored with this mindset. The individual is focused on completing actions and close-minded towards any information that leads to reconsidering the plans. However, individuals are tuned towards information that guides their actions towards their goals.</p>	<p>An actional mindset in designers may manifest itself in the form of the "Flow experience" defined by Csikszentmihalyi (1990) [14]. The actional mindset may be seen in the trailing end of ideation or during concept development. In these stages of the design process, designers work on defining and developing the concepts through prototyping and other methods. They are hence cognitively tuned to reject information which may lead them to question their choice of design direction. Alternatively, they are only concerned with information that leads to better versions of their concepts. Thus, the actional mindset in designers can be summarised by saying that they are 'Developing the solution.'</p>
<p>Evaluation Phase: In this phase, individuals evaluate the completed task and seek information that helps them assess it effectively. Primarily two questions are answered – 'Has the outcome been achieved by performing the planned actions?', And 'Does achieving the goal match the expected value?' Typically, when the goals are more elaborate, individuals must await the consequences of actions. Evaluating the outcomes helps in understanding the task's success and helps in future pre-decisional phases due to the newly found information from the evaluation.</p>	<p>In this phase, the individuals exhibit an evaluative mindset, which is the cognitive tuning towards information that helps to evaluate their actions. The evaluation is primarily about 'what is achieved' (outcome) and 'what is obtained' (consequence). Thus, the individual seeks information that allows assessing the quality of the outcome and the desirability of the consequence. The individual is open-minded towards receiving such information and is unbiased in analysing the completed actions.</p>	<p>When considering the design process, the evaluative mindset seems to be associated with concept selection and solution testing stages. In these stages, the designer is attuned to finding information to help the evaluations. Similarly, the designer is open-minded and unbiased towards the concept selection and testing outcomes. We can summarise the Evaluative mindset in the context of a design process as 'evaluating the solution'.</p>

We argue that given a certain design context, a designer exhibits some motivations and employs specific information handling strategies that align with each action phase in the Rubicon model. Such strategies can be analysed to understand the frugal mindset.

Therefore, designers working on solutions for MC were interviewed for this study, and the findings were qualitatively analysed. A qualitative exploratory study was found suitable because of the emergent nature of the phenomenon and the lack of sufficient foundational literature. Similar methodologies have been employed to understand design phenomena by other researchers [15]–[17].

Interviews were conducted with 12 expert designers and decision-makers who have contributed to developing some solutions for the MC. Subjects were interviewed telephonically following a semi-structured questionnaire and a strict protocol. The collected data were qualitatively analysed, and a set of strategies employed by designers were derived. The next section provides specific details of the methodology. The qualitative study results are discussed in Section 6.4. The discussion section of the chapter outlines the importance of the study, its connections with prior work and the implications for a systematic frugal design approach. Some limitations for this study and relevant future work are presented in the conclusion of the chapter.

6.2 Methodology

The subjects for the interview were identified through a combination of targeted, convenience and snowball sampling methods. Professional contacts were explored to identify notable designers and decision-makers of organisations working on solutions for MC. These contacts suggested other contemporaries and connected with them for our research. Furthermore, subjects were also identified through web searches in popular professional social media websites. Of 43 people contacted, 12 agreed to be part of the research.

The interviews were conducted telephonically by volunteers following a semi-structured questionnaire and a strict protocol. The protocol was developed considering the guidelines for ethics and best practices for a telephonic interviewing practice [18, p. 368]. The interviews were audio-recorded and analysed for quality, the pertinence of answers and adherence to interview protocols, after which ten interviews were selected for the qualitative analysis.

Before conducting the interviews, a semi-structured questionnaire was prepared using Gollwitzer's Rubicon model of action phases [13]. The interviews were audio-recorded and transcribed verbatim. The interviews lasted from 18 minutes to 90 minutes and resulted in 424 minutes of total recorded data with nearly 63000 words of transcribed text.

The interview transcripts were thoroughly read and then analysed through multiple coding approaches using the Atlas.ti® 9 QDA software. Literature suggests that an iterative approach for qualitative analysis is suitable when the underlying theoretical attributes of the studied phenomenon are unclear [18, p. 444]. Therefore, multiple coding methods were used to understand the data. First, an open coding approach was followed to develop a comprehensive list of codes grounded to the data following the Charmaz approach [18, p. 446]. Next, a focused and theoretical coding of the data [18] was done based on Gollwitzer's mindset theory of mindsets to identify insights from the data.

Coding is the process of generating 'codes' or 'tags' linked to the underlying data and allows for qualitative analysis. A code can be a word or a short phrase explaining the underlying data and capturing its essence [19, p. 3]. The code extraction and coding process is the primary way of making sense of textual research data. It is an interpretative exercise and depends on the researcher's worldview where certain 'lenses' are used to interpret the data [19]. In this analysis, quotations were extracted and coded if:

- An indication of an underlying mindset of the interviewee in a specific dialogue could be sensed.

- Participants explicitly spoke of any specific mindset needed for designing for marginal contexts.
- Participants spoke of challenges, inhibitions, successes or failures in their project.
- Participants mentioned how they accomplished certain design tasks.
- Participants spoke of any specific design process or stage which was interesting or challenging for them
- Participants narrated an incident which they felt was relevant for the design process
- Participants explicitly mention any aspect of the design or development process as important.

Total 560 quotations were extracted, and a two to five-word code was assigned to each that summarised the quote. After identifying quotations from the dataset, three iterations of ‘first cycle coding’ were conducted per the Charmaz approach [18, p. 446]. In the first iteration, we used an invivo coding approach [19, p. 91] to better understand the textual data. This iteration resulted in 216 codes associated with the quotation. In the second iteration, an open cycle coding method was followed [19, p. 100], which further distilled the invivo codes into more thematic versions, resulting in 112 codes.

Additionally, many codes from the first invivo coding were subsumed into others in the second iterations, and newer, more appropriate codes were added. In the third iterative coding, the number of codes was further reduced to 67 by combining conceptually similar ones into a set that could be analysed better. Each code was then described to clarify its meaning. Figures 6.2 and 6.3 are screenshots from the Atlas.ti® 9 Software that illustrates the selection of quotations and the coding process.

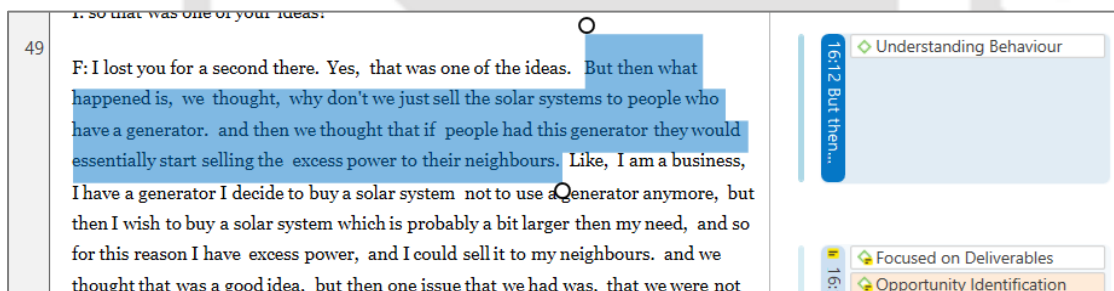


Figure 6.2: A Screenshot from the Atlas.ti® QDA software showing a selected quotation and the codes assigned to the quotation.

Search Code Groups		Search Codes		
Code Groups		Name	Grounded	Density
1: I have to Know State of Art (1)		U: Context Understanding	57	0
1: I have to understand the people (4)		Opportunity Identification~	38	2
1: Orientation to Accept Ambiguity (2)		C: Solution Proposal Detailing	30	0
1: Orientation to Satiating Intellect: (4)		Prototype and Test in Context~	26	2
1: Orientation to Serve Society: (3)		C: Product Design Detailing	26	0
1: Orientation to Understand Reality (8)		I: Solution Proposal Ideation	25	0
2: Orientation to Time Planning: (2)		I: Product Design Ideation	25	0

Figure 6.3: A Screenshot from the Atlas.ti® QDA software showing some codes and code groups used in the process.¹

¹ . In the screenshot, ‘Code groups’ is a functionality provided by the software to create groups of related code. ‘Grounded’ refers to the number of quotations that a code is attached to and ‘Density’ refers to the number other codes to which the code is linked.

Two 'second cycle coding' exercises were conducted after the three iterations of 'first cycle coding'. In a 'second cycle coding', a qualitative researcher develops a theory by connecting and categorising identified codes into existing or new frameworks. The first exercise followed a focused coding method [21, p. 213]. The results from the focused coding identified specific strategies related to each mindset in the Rubicon theory of action phases. These strategies are how designers working in MC attune themselves to search, deliberate and select relevant information that supports the specific mindsets of each action phase [9]. Figure 6.4 shows a screenshot of the focused coding result from the QDA software.

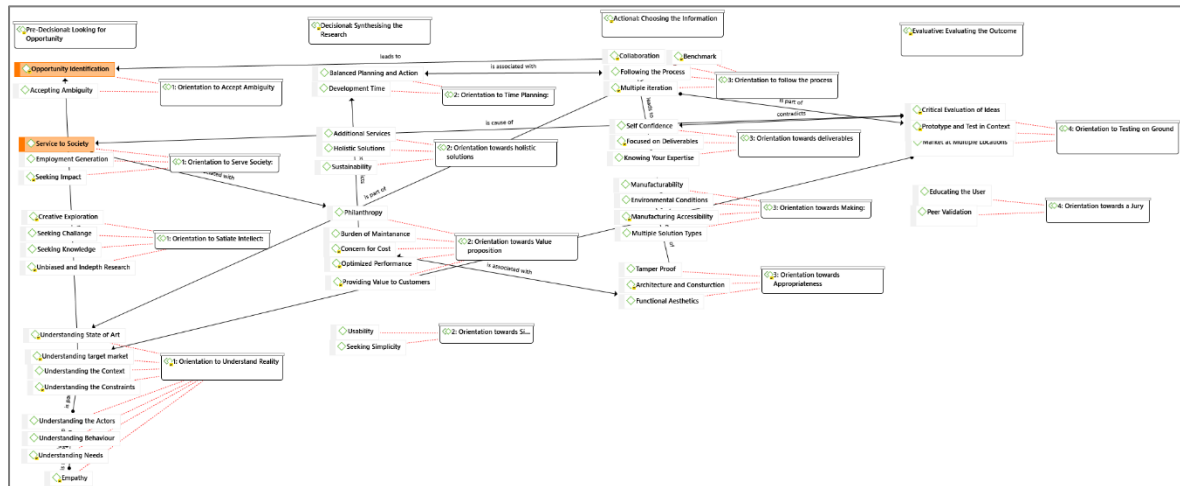


Figure 6.4: A Screenshot from the QDA software showing a map of the focused coding process. Each block is a code resultant from the 'first cycle coding' and shows how several codes are linked together and organised to form a theory.

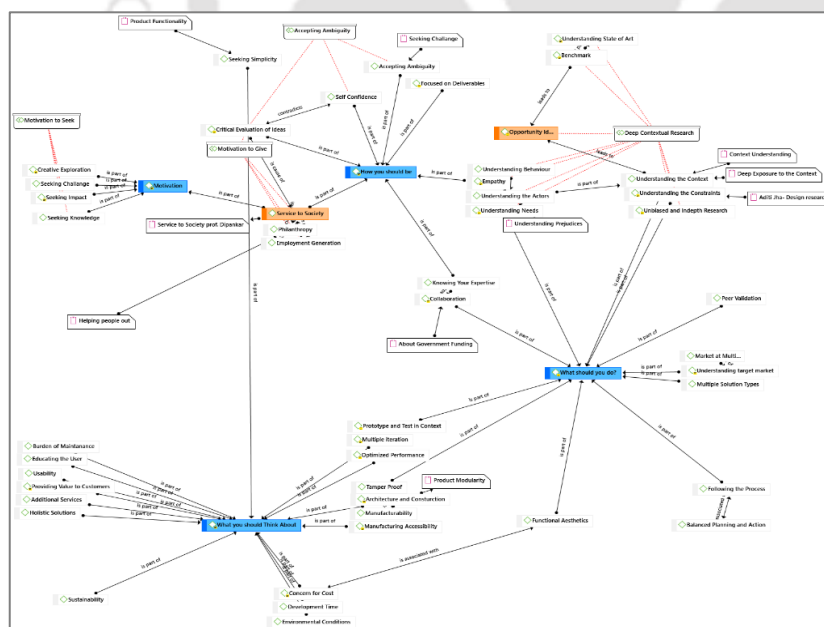


Figure 6.5: A Screenshot from the QDA software showing the result of the axial coding process. In this coding process, the links between the codes are developed to uncover latent theories from the data.

Another iteration of 'second cycle coding' was done using an axial coding method [19, p. 218]. Axial coding is a method of reassembling the data to determine dominant themes and theories. Axial coding is more helpful to uncover emergent theory from the data [19, p. 218].

Two primary outcomes emerged after using an axial coding method. Firstly, strategies that designers used for identifying new opportunities for design in marginal contexts were

found. Secondly, unique motivations displayed by designers working in MC were identified. Figure 6.5 shows a map view of the result of the axial coding process. The codes are linked together with other relevant codes to uncover theories from the underlying data.

6.3 Results

Table 6.2 shows the details of the interviews chosen for analysis after screening. Specific information has been removed to protect the identities of the interviewees.

Table 6.2: Subjects and details of the interview conducted.

Organisation Type	Product/Service	Interviewee	Details of interview
A Design consultancy	Agricultural Implements	Sudhir, Founder	Telephonic, 46 minutes
An academic organisation	Nanoelectronic devices for underprivileged	Dr Dipankar, Faculty and Lead investigator	Face to face, 89 minutes
A Socially oriented product organisation	Donkey milk soap	Rishabh, Founder	Telephonic, 66 minutes
A Healthcare ICT Solutions company	A maternal health monitoring platform	Aditi, Designer	Telephonic, 60 minutes
A Design Services company	Worked on ICT solutions for BoP context	Nikitha, Co-Founder Product designer	Telephonic, 31 minutes
A Design consultancy	Tata Swach, (as a consultant organisation)	Sateesh, Founder	Telephonic, 19 minutes
An Autonomous government organisation for innovation	Various products in NIF	Rishiraj, Designer	Telephonic, 28 minutes
An Energy services company	Energy products	Fabio, Co-Founder	Telephonic, 32 minutes
A company making farm irrigation products	Drip irrigation system for marginal farms	Dr Goutam, CEO	Telephonic, 42 minutes
ICT Product and service company	ICT and connectivity devices for low resource schools	Kareena, Content Manager	Telephonic, 29 minutes

The word cloud below (Figure 6.6) shows a sample of the most frequently used words in the transcript after removing non-relevant words and considering inflected forms (word frequency capped at 20). The word cloud provides a flavour of the overall discussion with the experts.

experience. Designers also acknowledge the additional pressure and possibility of failure due to such ambiguity. However, they are confident in their ability to deliver a good solution. This self-confidence makes them able to reconcile the ambiguity in the design process.

In an example, Sudheer could not figure out the solution to a problem, yet he kept working on it to find a solution. Sudheer says,

“so the mechanism till that we could not develop it. I tried several times of iterations, but we could not reach close to that, so at times we fail”.

Technical limitations, knowledge, and lack of experience are not considered barriers to identifying solutions. Sudheer says,

“I’ll tell you one of my very important projects, called biomass gasifier-based power plant. I never knew a single word of this... client said, Sudheer you take up this project, I’ll give [you a book to read], and then you design the product...and I did it successfully.”

Similarly, Fabio says that his team knew what they did not know. He says

“...we were very aware that we had no experience in this sector, we had no experience in the country. so I think we knew that we didn’t even know.”

Regarding confidence in tackling ambiguity, Fabio says,

“a lot of people, they are very confident; otherwise, they would feel overrun, I guess. but if you do have the right thing, and you can sustain the pressure.”

Most designers echoed a similar emotion where they directly or indirectly suggested that they are subject to more stress due to the increased ambiguity in the context.

- **Orientation to Serve Society:** Several experts indicated that they view the projects as a service to society. Typically, their motivations are to positively impact the context than for intellectual or monetary gains. When identifying design opportunities, such motivation was a key factor for deliberating on the goal’s desirability.

When speaking about the capabilities of clients, Sudheer says,

“I know that these small people, who would...get benefited, out of this design. so, this was an intention in, sometimes helping, these people and clients, and new startups and all, so and I feel like helping them and all.” (sic.)

Experts also seemed to favour opportunities with a higher scope of creating a positive and lasting impact in the context. For example, Fabio looked at the state of the electricity access in an MC and the impact of a microgrid energy solution before starting the project.

Orientation to Satiat Intellect: Designers working in marginal contexts sought and selected opportunities that fulfilled their creative and intellectual aspirations. They also seem to have an affinity for opportunities that challenge their capabilities. Fabio, when explaining why he chose to go with a challenging project, says

"[because] it was a challenge, and we definitely like challenges. it was fun, it was real, it was different, and it was potentially very big".

Satish also says that his affinity towards his project came because it was challenging. Similarly, Dr Dipankar started looking for project opportunities in the most challenging areas in his domain.

Similarly, designers working in MC had an affinity towards opportunities with a scope of obtaining or generating new knowledge. The scope of conducting novel research was also a driver for many experts, and they placed high value in doing original research as part of the design project. Satish says that 80% of his project time is dedicated to research and 20% to design in his projects. Aditi echoes this sentiment by saying,

"...on a strong research foundation is how good your product will be."

Orientation to Understand Reality: Expert designers unequivocally stress the need for "understanding the reality" when designing for MC. Understanding reality means gaining first-hand information, insights and knowledge about the context and all other aspects which may affect a solution in the context. This information handling strategy is the primary driver for finding novel and contextually appropriate design opportunities.

Expert designers place a high value in uncovering the nuances and unique challenges presented by an MC. A suggested strategy was to deep dive into the context by working and participating in daily activities. For example, Kareena shared that her company's founder spent a significant time teaching in remote schools before coming up with the idea of a digital learning solution. Similarly, Aditi travelled to multiple villages and stayed with the people to understand their culture, needs, behaviours and motivations.

We found three distinct ways in which the designers engage with the context for understanding reality. Firstly, it is through interviews and discussions. Second, it is by enlisting the help of people who are embedded in the context, such as NGO's and public organisations. And finally, through participation in the day to day activities of the people. In Aditi's project, she participated in the hospital activities by accompanying nurses, doctors and patients through their day. Talking about her project, Aditi suggests,

"it's always important to keep talking to people. Not only from different fields, but also the patients that you're visiting, or the nurses, or the doctors. Understand [them], get into their shoes, that's more important."

Another insight was that designers try to uncover people's inhibitions, aspirations, and behaviour and aim for solutions that a larger set of people can use. Expert designers critically analyse people's behavioural patterns, rituals, and cultural activities in the context. Rishiraj goes as far as to say:

"We have different mindsets of each individual state."

Understanding user behaviour leads designers to assess the feasibility of solutions in the context. In a particularly interesting case, Fabio had to abandon an opportunity of selling solar systems to people who had generators because he realised that they would start selling the excess power to their neighbours.

A part of understanding the reality is knowing the state-of-art of the technology being pursued. Extensive literature research and prior art study are used to evaluate novel opportunities. Depending on the nature of the project, the prior art search may be simple or significantly advanced, e.g. in the case of Sudheer's project, he looked at existing solutions on the internet. In contrast, Dr Dipankar used nanotechnology for designing medical devices for MC.

6.3.1.2 Implemental Mindset and Strategies for Marginal Contexts

According to Gollwitzer's theory, an individual has an **implemental mindset** during the decisional phase of goal pursuit. When having an implemental mindset, designers are concerned with **planning and synthesising the research**. Thus, for a design project in MC, a designer attaches information to create new ideas or plan the project.

Four unique strategies were found to be employed by designers for supporting an implemental mindset. These are Orientation to Time Planning, Orientation to holistic solutions, Orientation to providing value and orientation towards simplicity. Following are the details of each of the identified strategies:

- **Orientation to Time Planning:** Designers working in MC plan their projects to strike a balance in the time spent for execution and synthesis of the research. Fabio, for example, suggests that a balance has to be attained wherein designers do not spend an unnecessary amount of time synthesising research and do not jump into the field for execution without gaining a good understanding of the context. He adds that such a balance is tricky to get right but essential for ensuring fewer failures on the field and safeguarding a designer's reputation.

Additionally, Expert designers tend to continuously find ways to considerably reduce the development time when planning the execution of a project. Sometimes this is driven by client requirements, and at other times, it reduces investment and eventual product costs. As Rishiraj points out, this may lead to granular decision making.

- **Orientation towards holistic solutions:** Expert designers in MC consider developing holistic solutions and plan their project outcomes accordingly. Designers strategically select opportunities to include implementation services, additional products or other lifecycle services to support their products. For example, Kareena's company planned to offer services to install new products in schools. On the other hand, Fabio's company sells lighting fixtures and appliances to use with the electricity they sell. Similarly, Sudheer and Satish vouch for after-sales services being the key criteria for sustaining a product in marginal markets.

Additionally, experts actively plan their projects to attain ecological and socio-ethical sustainability. Aditi, for example, says that they are aware of potential e-wastes generated by the usage of their medical device and actively try to implement ways to mitigate it. When discussing the major challenges for her project, she said:

"if we are using those layers, are those layers very eco-friendly? Can dispose of well? Can we take another step for disposing off responsibly?"

- **Orientation towards Value proposition:** Experts are acutely aware of the exact value proposition needed for the people and thus plan their project and its implementation

considering it. In the interview with Fabio, he discussed why the Tata Nano failed. He commented that it failed because Tata Nano was considered a cheap (affordable) solution, whereas people in marginal contexts do not want cheap solutions. He says, *“people did not want a cheap car; they wanted a good car”*.

Experts strategically plan processes and select ways to reduce overall product cost, client investments and development costs. Sudheer, for example, discusses how low investment manufacturing methods were chosen for production because he knew his clients could not afford high-cost processes.

However, unintuitively, experts were less concerned with the affordability of their solutions. They do take necessary measures to ensure the lowest cost solution possible but try to employ other ways to make the solution affordable in MC. They suggest that novice designers do not think designing cheap solutions either. Fabio says,

“even if your customers have really no income, it doesn’t imply that they want something cheap.”, And “you don’t want to be selling to them the cheapest possible thing; you want to sell the best possible thing.”

Orientation towards Simplicity: Designers tend to gravitate towards simplicity when selecting potential opportunities, planning the project or synthesising the solutions.

It was found that simplicity is pursued in multiple ways. Experts consider simple ways to identify and evaluate opportunities, e.g. Fabio suggested a simple (and aggressive) method of critical idea evaluation by ‘trying to kill’ the idea.

Similarly, simpler solutions for emerging design problems are preferred, e.g. in Aditi’s kiosk project, the kiosk needed to be stationary for the users but portable for the staff. So, they made a circular base on the kiosk that could be rolled by two people rather than add expensive caster wheels.

Experts also considered simpler working principles when tackling the overall design. For example, in Satish’s water filter project, he chose a simple and proven working principle to develop a filter lock after its duty cycles. Satish also chose a simple form for the water filter to be disassembled and nested during transportation, thus reducing the overall shipping volume significantly. On pursuing simple solutions for design problems, Sudheer said,

“when you start getting simpler solutions, you will be the most happiest person; actually, you have solved the solution [in] no time, [in] no cost, [with] no resources.” (sic.)

6.3.1.3 Actional Mindset and Strategies for Marginal Contexts

An **actional mindset** is associated with **implementing the goals** set in the prior phases. The individual focuses on completing actions and is close-minded towards any information that may rework the plans. Considering the goal of designing a solution, we see that the actional mindset aligns with the concept development phase of the design process.

Four unique strategies were found that experts working in MC employed to support an actional mindset. These are orientation to follow the process, Orientation towards deliverables, Orientation

towards Making and Orientation towards Appropriateness. Follow are the details of each of the identified strategies:

Orientation to follow the process: Experts emphasised a design process focusing on collaboration, benchmarking, and iteration when designing the solutions for MC. They rejected information that could lead to deviation from such a process.

Experts affirm the need to collaborate with users and agencies embedded in the context. For example, Rishiraj collaborated with grassroots innovators to understand the design requirements for solution development. Rishabh collaborated with users to understand their daily lives and problems and find underutilised resources. On the other hand, Nikita collaborated with NGO's who already had experience working in the field.

Collaborations are also common for filling a gap in specific skillsets. For example, Dr Dipankar collaborated with entrepreneurs for developing a business model around the technology he developed. Similarly, Fabio and Kareena collaborated with external companies to provide additional services with their solutions.

Benchmarking was another aspect of the design process that experts did not compromise. Experts continuously compare and benchmark their solutions to direct design activities throughout the design process. Benchmark is done to understand the solution's form, technology, working principles, market and business aspects.

For example, Satish benchmarked his mammography machine with internationally available machines worth 18 lakh rupees to estimate his product costs and choose the right features for the product. Similarly, Sudheer compared the costs of domestically available machines and decided the product's pricing for his client. In both cases, the final product was an order of magnitude cheaper than the existing ones. Satish also highlights that benchmarking technologies leads to novel working principles that would not have been otherwise explored.

Finally, nearly all interviewees emphasised the importance of iterative prototyping. Iterations were diligently done even when contextual constraints stopped designers from pursuing them. In the case of Fabio, since he did not have access to prototyping facilities in the context, he chose to develop prototypes in Asia and then test them in context. Additionally, each iteration is tested rigorously and in close to actual conditions. We found that experts enlist the help of various laboratories and testing facilities to test their prototypes extensively. Satish said that nearly 2500 prototypes were created and tested for his water filter project in an outlying example.

- **Orientation towards deliverables:** Experts are acutely focused on the deliverables of the project once the design plan is put into motion. Information that contradicts the planned deliverables is rejected. This focus allows them to solve one problem at a time and create novel collaboration opportunities. Fabio says,

"We found that it was important to be focused on one problem. And we saw that solving that one problem would have enabled others to come in and use our solutions to solve other problems."

Experts are also keenly aware of their skill, knowledge and limitation when creating the deliverables. In cases where their capability meets the project needs, they continue

developing multiple iterations to arrive at the best solutions. In situations where their skills fall short, they immediately identify appropriate collaborators. Fabio says

“Ideally, you want to have a different person for each skill set... where each person is specialised in something and fixes those problems without burdening everybody.”

Awareness of one’s skills leads experts to be continuously updated with state of the art in the domain, novel hiring strategies, infrastructure upgrades and novel concept development strategies. Both Dr Dipankar and Aditi say that their team was developed considering the complementary skills required to develop their solutions.

Finally, Experts were surprisingly self-confident despite knowledge of lacunae in their skillsets. They were confident that their chosen directions, teams and working methods would yield desirable results. Kareena, for example, says,

“We have had a lot of people come on board that have had their doubts. There are people who still have their doubts. But, I still believe that it is a really great solution.”

- **Orientation towards Making:** Experts extensively focus on prototyping and ‘making things’ as a strategy for implementing the actional mindset. All experts we interviewed emphasised the importance of prototyping and making.

Iterative prototyping allows experts to understand the manufacturing challenges and product feasibility and develop easily implementable process plans. Additionally, iterative prototyping can help understand the impact of environmental conditions and inadequate infrastructure on the designed solution.

However, there are some challenges to making, which experts carefully consider when executing their project plans. Fabio, for example, says,

“Hardware development is a very expensive and complicated thing to do, and it requires multiple iterations, and in our particular case, we had no supplier whatsoever. So, we found ourselves essentially going, develop in Europe, and doing some manufacturing in Asia, and then testing this prototype, with every iteration to come out. It was very expensive.”

Similarly, Rishiraj and Aditi both highlighted the lack of vendors in India for their specific products. As a strategy, they suggest the development of vendor lists specifically to support designers working in MC.

- **Orientation towards Appropriateness:** Experts extensively focus on product architecture, modularity, functionality, aesthetics and reliability when developing the product concepts and prototypes.

Both Sudheer’s and Satish’s products were designed with modularity in mind, wherein parts could be easily swapped out for another or modified to achieve alternative functions. Sudheer highlights using off-the-shelf parts and repurposing them to suit certain product functions as a valid strategy for significantly reducing product costs. Additionally, designers increase the product’s chances of being locally produced by using readily available parts and

materials in the context. Sudheer suggests another way of reducing costs significantly by creating integral product architectures, i.e. designing parts, components or modules which can fulfil more than one function.

Experts emphasise the importance of reliability in product architecture design. They are aware of the harsh environments and lack of knowledge of their user. Products are thus designed to be robust to environmental fluctuations and user error. Some experts suggested making the solutions tamper-proof if they are to be used in public spaces. Such measures can be a way to facilitate certain user behaviours as well. For example, Satish designed the filter cartridges for his water filter to lock up after their duty cycle to ensure that the user is 'forced to change it' and consequently do not drink unsafe water. In another instance, Aditi's team redesigned the charging mechanism to eliminate the often-misplaced external charger from the kiosk.

Despite the sharp focus on developing the architecture, experts insist on designing aesthetic products. However, aesthetics is pursued as a functional requirement. i.e. Experts seek to emphasise the functionality, usability, and robustness of the product through its form. Satish, for example, says,

"it's not just about making a pretty looking product, I think [about], the way the product will be shipped to them, the way the product will be assembled, the way the product will be maintained."

Similarly, Aditi says,

"aesthetics is important because, you know, I shouldn't scare my patient.". She adds, "there is a lot of things related to psychosomatics too. Here patients are already in pain, and you are attaching some sort [bulky device with lights, battery and wires on them], People get scared."

6.3.1.4 Evaluative Mindset and Strategies for Marginal Contexts

According to the theory of action phases, an individual has an **evaluative mindset** during the final phase after completing all planned actions. During this stage, the individual **assesses outcomes against the expected value and awaits the consequence** of the actions. Designers with an evaluative mindset are concerned with concept selection and solution testing.

Two unique strategies that designers working on solutions for MC employ to support an evaluative mindset were identified. These are Orientation to Testing on Ground and Orientation towards a Jury. Each of these strategies is employed to effectively evaluate the solution, the executed design process and plan further work related to the project.

- **Orientation to Testing on Ground:** Prototype testing is the primary means designers use for concept evaluation and understanding success. Experts are thus open-minded in accepting information that helps them in extensive prototype evaluation and testing.

Additionally, prototype testing is an integrated effort where the effectiveness of the marketing plan, distribution plan, product design and other system-level aspects of the solution are also evaluated. Kareena shared that the prototype testing phase overlapped with several preliminary marketing activities in her project. She says,

"We started talking to a lot of teachers, telling them that we have this product, but it is still in the testing phase in the pilot phase and all. Would you be interested in using it and, you know, what are your thoughts?...we are funding about 80 schools in India right now...we just give [the solution] to them...free of cost... so the more users we got, the more we were able to establish the fact that this is actually really working, people really like this."

Typically, the process of prototype testing on the ground is accompanied by extensive discussions with the actors in the context, laboratory testing and field testing of the solution. Some experts like Dr Dipankar and Sateesh also advocated a scientific approach to prototype testing. Experts viewed critical evaluation of the solution as a moral responsibility rather than just a step in the design process

Experts also highlighted that certain aspects of user behaviour are only evident after the solution is implemented and used as intended. Aditi, for example, found out about the myriad possibilities of vandalism that can happen in her Kiosk design only after it was left in the context for use as intended. She says,

"I remember... [with the] kiosks been set up; the chargers were [stolen], ok? so, every time we have to replace that and give them a new charger. Now...we made a system where the charger is locked inside, and the wire is extended."

Several experts illustrated that testing on the ground generated unexpected user feedback, which led to significant improvement in design. Experts also favoured extensive on-ground testing of the solution for their personal contentment. Dr Dipankar, for example, says he approaches testing with a sceptical view so that he can make meaningful progress afterwards. He says,

"[being suspicious of your own results is what] makes you a very good researcher, scientist, technologist. because until and unless you are sceptical about your results...you are not going to progress after that."

- **Orientation towards a Jury:** The final strategy experts employ to support an evaluative mindset is their inclination for review by their peers, experts and visionaries in the context.

As a strategy for peer review, many experts said they routinely send their designs in exhibitions, contests and publications. Rishiraj discussed how he exhibited his solutions at a National expo to gain feedback from experts from various fields. Similarly, Satish mentions how he always sends his solutions to international design contests and has won multiple times. Rishabh fondly recollected the various avenues where he presented his solutions and won fiercely competitive awards.

Such recognition reinforces the appropriateness of the proposed solutions, provides gratification, and gives much-needed pointers for marketing the solution. Such reviews and awards also enable designers to create general awareness of the product and connect with funding agencies and experts. Rishabh, for example, says,

"after winning [the award] we met many people. Like they were congratulating that 'your idea is superb'. And when people come to you, and they say that 'your idea is something else', 'you are doing very much different'...when the mentors and the guest also want to connect with you, they give their business card...just

connect with them, for marketing purposes, for fundraising purpose, for financing, at that point we realise that we are doing something good.”

We find that expert designers are generally oriented to use opportunities where peers, experts and user can evaluate their solutions.

6.3.2 Results of Axial coding: Opportunities and Motivations

Through the process of Axial Coding, we arrived at two major findings. First was a general understanding of the strategies used by experts for identifying novel design opportunities. Second, are the motivations of designers for developing solutions for MC.

In a typical design process, ‘opportunity identification’ is the process of finding new ideas for product development and lies at the fuzzy front end [20]. However, it was found that in frugal design projects, the activity is continuously conducted until a solution is finalised. New ideas are generated as requirements evolve, new requirements are identified, new product features are selected, and the holistic aspects of the solution are detailed. This process is referred to as ‘Opportunity identification’ in frugal design for MC. Thirteen strategies that designers employ in MC for opportunity identification were found through the analysis.

Designers’ motivations play a key role in building a frugal mindset and pursuing appropriate solutions for MC. In the face of myriad constraints presented by MC, these motivations provide a reason for designers to persist towards their goals. Two types of motivations were uncovered through axial coding. First is the ‘Motivation to give’, where the designers are motivated to work on projects to serve society. The second is ‘Motivation to seek’, where designers are driven to fulfil their internal self-actualisation goals.

In the following two sections, we discuss the 12 strategies of opportunity identification employed by the designers and the motivations that drive designers to find appropriate solutions for MC.

6.3.2.1 Opportunity Identification in frugal design projects

We found that expert designers undertake extensive opportunity identification and problem finding activities even when the client brief is clear. Opportunity identification is conducted throughout the design process with different goals at every design phase. One expert designer suggests that nearly 80% of the time is spent on such research.

Results indicated that opportunities for developing novel solutions are identified during the initial phases. In contrast, opportunities for improving and detailing the solutions were identified in the later design stages.

We found that designers used certain ‘lenses’ when looking at new information for identifying design opportunities. These ‘lenses’ can be considered as overarching considerations typical of a designer with a frugal mindset. The ‘lenses’ also help mentally evaluate the appropriateness of new opportunities. These are:

- Empathising with the **Target Users** and knowing their capabilities when selecting a new design opportunity.
- Considering the **Cost implication** on design, development and solution usage when encountering new information and evaluating opportunities.
- Selecting opportunities that are pertinent to a specific **Geographical Boundary**.
- Selecting opportunities with an awareness of **Team Expertise** and experience.
- Gravitate towards opportunities that can improve the **Usability of Solutions** and make them generally appropriate to the context.

These five lenses supplement the specific strategies employed by designers when identifying novel design opportunities throughout the project. These twelve opportunity identification strategies are discussed below.

- 1 Experts emphasise that **deeply embedding themselves** in the context by working and participating in various activities in situ provides awareness and *groundedness* of the issues in the context. Unique and pertinent design opportunities can be found through such an approach. In the case of Kareena, their company's founder taught in a remote area without internet access which made him aware of the unique challenges and eventually led to identifying a new product opportunity. In the case of Fabio, an opportunity was identified during a trip through MC, where he eventually executed his solution. Furthermore, Fabio worked in the context for nine years before developing the solution. Aditi Mentions that their companies founder travelled for a year around and explored contexts where cases of infant mortality were high and then identified a novel design opportunity.

However, such long-term engagement may not be feasible for all designers. In such scenarios, experts suggested gaining first-hand experiences through field trips, doing short term work with existing agencies and collaborating with people in the context.

- 2 Opportunities can be identified by **analysing existing solutions**. In the case of Kareena, they **analysed the usage pattern of their existing solutions** to identify opportunities for a novel product. She says

"so, we already had Class Club in place, it's been almost three years, but it is quite complicated and difficult to use. and we wanted something that was also very simple and easy to use,"

Similarly, Aditi identified novel opportunities by analysing existing solutions and **empathising with users**. In the case of Fabio, he envisioned how people would use the solution he already designed by understanding people's behaviour and usage patterns with similar solutions.

- 3 Opportunity Identification can also be done by **considering the expertise of the team**. Aditi Says,

"so, since we are solely based on electronics, and we thought of coming up with the solution. [related to electronics]".

Expert select collaborators and agencies for helping in identifying novel opportunities.

- 4 Another strategy for opportunity identification highlighted by experts is to seek out issues currently **not solved by existing social or governmental programs**. Rishabh, for example, suggested that their team go through a list of skill development and other such programs to identify the area where governmental intervention is less. This process enabled them to position their solution in a niche area and potentially have a greater impact.
- 5 Understanding the **underutilised resources within the targeted community** in the context can also help find new design opportunities. For example, Rishabh discovered that donkey milk was considered a waste by the donkey owner community since no one was interested in purchasing it. Mostly the donkeys were used for transportation in the brick-making industry. Making a 'collection of resources' users had and researching alternate ways to use them helped their team discover a strategic design opportunity. Eventually, the team settled on developing cosmetic products using donkey milk and positioned it as a socio-ethical and natural alternative to existing products.

- 6 Another method of opportunity identification is **understanding the imminent need of the geography** where the context is situated. For identifying new opportunities for medical devices, Dr Dipankar considered prevalent diseases in the geography where he was developing the solution. He says,

"When we started, we wanted to pick up a disease which is Northeast specific. This was the first thought that came."

By closely analysing the pertinent problems in the geography, Dr Dipankar found the prevalence of alcoholism, pancreatitis and diagnostic challenges, which later became the focus for developing medical devices.

- 7 Experts also identified new opportunities by **seeking prohibitively costly solutions** and conceptualising low-cost alternatives to such solutions. Consequently, excerpts suggest using cutting edge technology to develop such low-cost alternatives. For example, Dr Dipankar employed state of the art nanoscience technologies to replace existing high cost medical diagnostic devices.
- 8 Opportunities were also identified organically as the team worked on a specific design problem for long durations. Dr Dipankar provides an example of **Organic Opportunity Identification**, stating that the funding agencies, team members with complementary expertise, and external collaborators suggested new diagnostic tools when developing point-of-care medical devices. Nikita also highlights how their team identified the opportunity for a new product called 'School wifi' when working on another product. Such organic opportunities identification seems to be accelerated when the design team:
 - has gathered enough expertise in the problem domain
 - have continuous discussions with supporting agencies and benefactors
 - has access to infrastructure for exploring the problem domain
 - are already working on a solution in a similar problem domain
- 9 **Personal Background and Expertise** plays a vital role in the identification of opportunities. Experts discussed how their experience with social or medical problems at a young age led them to consider solving these issues when seeking new opportunities. Aditi mentions how her role as a teacher crystallised her confidence in a digital solution for rural and marginal schools. Dr Dipankar's 'inherent knack' for all things chemistry, medicine and pathology led him to analyse the lacunae in the domain and seek pertinent opportunities which his expertise could solve.

- 10 Another common strategy for opportunity identification was **Interviewing the stakeholder** in the scenario. When clients approach designers with defined briefs, expert designers spend a significant amount of time discussing and analysing the problem with the clients. Nikita Says,

“we go sit with the industry; we go sit with the clients, try to understand what challenges are they thinking, is happening in the industry.”

Similarly, Aditi’s team spoke to the patients, doctors, nurses, hospital staff, and administration to identify new product features. They empathised with each stakeholder and analysed how their actions may affect a solution, which led them to identify specific opportunities for product design.

- 11 Identifying opportunities can also be done by **collaborating with organisations** that already work in related areas. Nikita highlights that they identify organisations with a long experience working in a sector and seek to collaborate with them to identify an opportunity or understand a problem.
- 12 **Understanding actor behaviour** is another way that can lead to the identification of specific opportunities. Aditi’s team studied how actors (users and stakeholders) behaved around existing solutions and the context while designing a medical product. She found that the hospital staff tried to cut corners and save money when using non-critical disposable items by reusing them. A knowledge of such behaviour led their team to design their solutions appropriately.

6.3.2.2 Motivations of Designers Working in Marginal Contexts

All experts shared their motivations for pursuing projects in MC despite the known challenges and constraints. These motivations are a critical aspect of the goal-driven behaviour of designers. Motivations lead to specific information handling behaviours, which eventually develops a frugal mindset appropriate for designing solutions in MC.

Some literature creates a distinction between ‘Intrinsic motivations’ and ‘extrinsic motivations’ [21]. Intrinsic motivations are internal forces of an individual striving to achieve a goal, whereas extrinsic motivations are similar to external incentives. An example of extrinsic motivation in design projects for marginal contexts can be the scope of making profits. Examples of intrinsic motivations may be a thirst for knowledge and the betterment of users lives. Both types are undoubtedly necessary for better executing any design activity. However, we argue that intrinsic motivations manifest as frugal mindsets and are pertinent to the analysis.

We found four unique intrinsic motivations among the experts we discussed. These can be understood as the reasons designers pursue projects in MC despite the seemingly additional difficulties. Following were the motivations identified:

- 1 **Seeking Social Impact:** Expert designers were motivated to see their solution create an impact in the context. This, in turn, creates a positive feedback loop motivating them to pursue the solution further. Experts generally identify the value of a solution by how much changes it can bring in an individual’s life. Some also consider the awareness created by a solution as a component of positive impact. Overall, Designers are motivated by the

potential to improve the lives of the actors in the context. Dr Dipankar makes an apt statement that encompasses the thinking. He says,

“my motive in this entire thing is that, so when you do service to people, you get a different type of satisfaction. [Even] if one person out of your technology is benefited... it leads to job satisfaction.”

Creating an impact is also equated to ‘giving back to society by several experts. Designers can be motivated by the prospect of helping out a single person as well. Sudheer highlights this aspect when he describes how he designed a product for a grassroots innovator who lacked product development skills. He says,

“I know that these people, who would, [take] very little of my time, and they get benefited out of this design. So, this was an intention in, sometimes helping these people.”

The motivation to extensively manifest itself during idea evaluation. Experts tend to evaluate and select ideas that can serve the larger population and are suitable for the ‘greater good’.

- 2 **Seeking a Challenge:** Designers were motivated to pursue projects in MC due to the unique challenges provided by the scenario. Contrary to conventional thinking, constraints are seen as a trigger for creative problem solving rather than inhibitions to design and development. Regarding the development of an award-winning water purifier for India, Satish says,

“[we did the project because] it was extremely challenging, to create a product which will not use electricity [and yet] have the best efficacy in purification...so that is why we took it up as a challenge, and we knew that it was not going to be simple.”

Even during opportunity identification, designers tend to gravitate towards the more challenging problems, e.g. Dr Dipankar says that their primary objective was to identify a challenge first and then identify problems in the area to solve.

- 3 **Seeking Knowledge and Creative Satisfaction:** Designers are driven towards projects for MC due to their curiosity and thirst for knowledge. Most of the experts indicated that there is much knowledge to be gained from designing for MC. They also attached qualifiers to their knowledge, stating that it was more practical, socially relevant, and therefore more satisfying to acquire. Experts seemed fascinated with the opportunity to explore new areas of knowledge, geography, problem domains and scope of academic enquiry.

Similarly, designers are motivated by the scope of ‘creative satisfaction’ when designing for MC. Due to the challenging nature of the context and the numerable constraints, a design project typically poses significant creative challenges for the design team. These creative challenges usually arise in the form of contradictory requirements such as lowering cost significantly but fulfilling all the users’ needs or providing solutions at low investment cost but using mass manufacturing methods. Designers working in marginal contexts actively seek projects which provide such challenges.

- 4 **Philanthropy and Goodwill:** Most experts indicated that they approach design projects in MC with a philanthropic perspective. They understand the resources limitations of both

users and clients and are willing to defer their immediate monetary gains in most situations.

Sudheer highlights this aspect by sharing specific anecdotes about grassroots innovators, startups, MSME owners and personal friends who approached him for his design services. He says that it is an honour for him to help people with his design knowledge. Kareena also says that their solution is being given to clients for free, she says,

“so, we started, we are funding about 80 schools in India right now...so we just give it to them free of cost, in fact.”

Similarly, Aditi's company provides pregnancy monitoring services with its medical device free of cost.

In some cases, the designers compensate for such a decision by generating supporting funds from benefactors, government agencies and hosting organisations. Sudheer, Rishabh and Rishiraj all agree that the motivation for such a project can be attributed in part to acknowledgement for their philanthropic contributions and design services.

Overall the analysis indicated that monetary gains and similar extrinsic motivations are less important for designers working in MC. Designers were less concerned with the scope of business and more with the scope of change in the context when starting their projects. However, this did not mean that they disregarded the profitability aspects of the project altogether. Profits were one of the extrinsic motivations for designers (Others were peer validation and awards). However, these extrinsic motivations came into effect towards the latter project stages and after most intrinsic motivations were satisfied.

6.4 Discussion

This chapter presented the outcomes of a study to understand the phenomenon of a “frugal mindset” in designers developing solutions for MC. Semi-structured interviews were conducted with twelve experts with experience in developing various solutions for MC. Interviews were then transcribed and analysed using qualitative coding methods described by Saldaña [19]. The methodology was found suitable due to the study's exploratory nature and a lack of existing theories describing the phenomenon.

Relevant quotations were extracted from the interview transcriptions after a thorough analysis. These quotations were then coded using an iterative ‘first cycle coding method’ following Charmaz's approach [18, p. 446]. The ‘first cycle coding’ resulted in a list of 67 codes that described the 560 quotations extracted from the interview data. These codes were then used for ‘focused coding’ and ‘axial coding’ in a ‘second cycle coding’ process [19, p. 207].

The results of the focused coding produced insights about the phenomenon of frugal mindset. Specifically, several unique strategies for supporting the mindsets in each action phase of Gollwitzer's theory of action phases [9] were identified. Based on these, a ‘Frugal Mindset’ is defined in the context of this research as follows:

A 'frugal mindset' is an overall mindset that emerges in a designer who employs these unique strategies when designing appropriate solutions for marginal contexts to satisfactorily meet users' needs.

In other words, a frugal mindset is the sum total of the cognitive processes that support the task of "designing appropriate solutions for marginal contexts" and the goal of "creating solutions that satisfactorily meet stakeholder needs". The identified strategies support the development of such a frugal mindset. Figure 6.7 below shows a visual representation of the results.

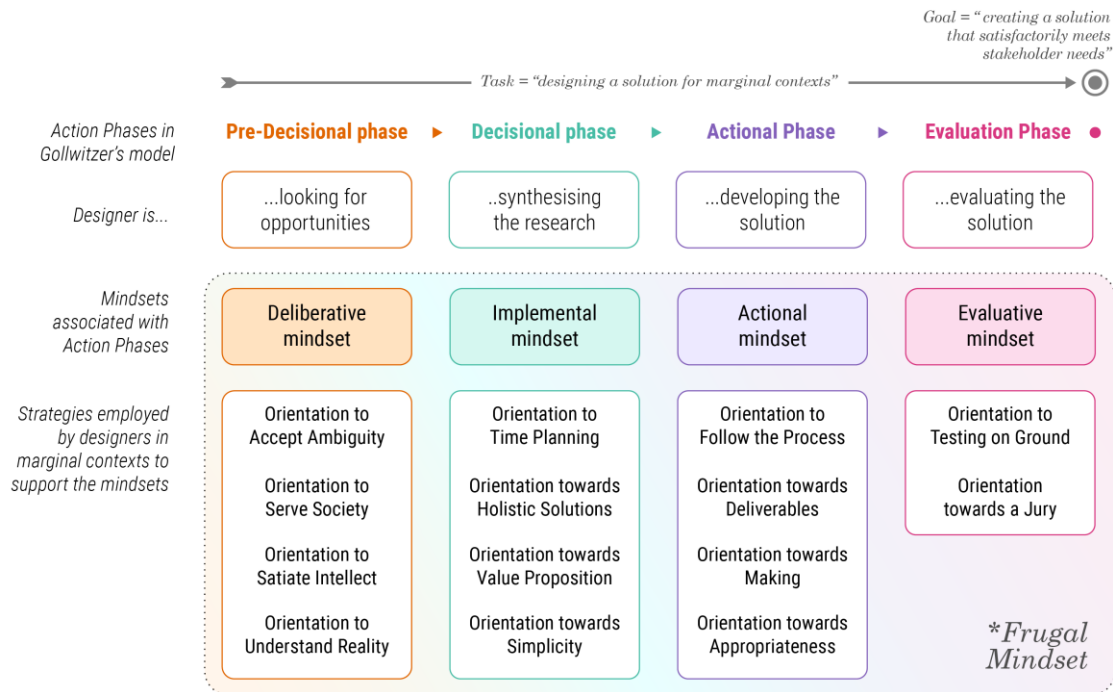


Figure 6.7: Strategies for Frugal Mindset: a visual representation of the results.

In another iteration of the second cycle coding, an axial coding process was used to identify emergent theories from the underlying data. The results of the axial coding were a set of strategies employed by designers when identifying novel design opportunities throughout the design process.

In a typical design process, opportunity identification is a stage at the fuzzy front end of the process [20]. However, the outcomes of this study indicated that for frugal design projects, designers constantly engage in opportunity identification activities throughout the design process. Opportunity identification activities are used to identify novel design directions, system-level strategies, product features and even evaluate design ideas. As a result of the study, twelve unique strategies for opportunity identification were identified that designers used when creating solutions for MC. In addition, a set of 'lenses' which designers use to assess information and insights were also identified. These lenses can be understood as overarching considerations used to mentally evaluate the appropriateness of new design opportunities. Figure 6.8 shows a visual representation of the results of axial coding.

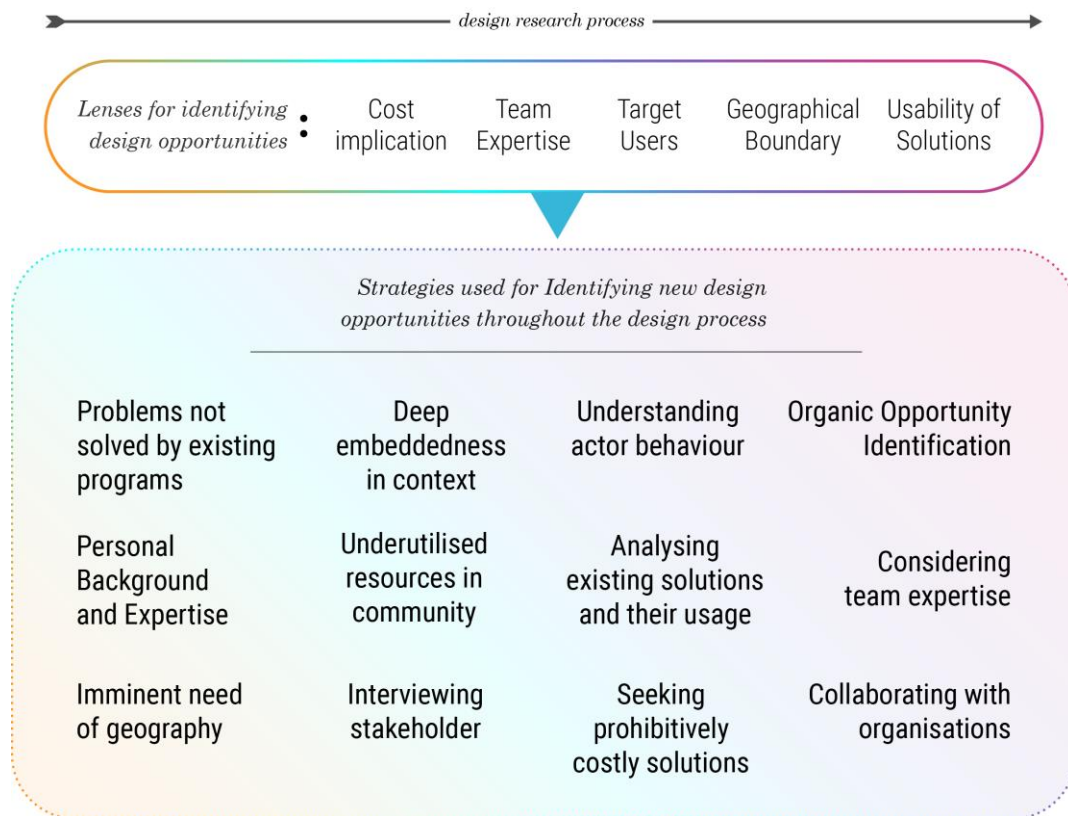


Figure 6.8: Lenses and Strategies employed by designers for identifying opportunities in design projects for marginal contexts.

Finally, a key finding of the axial coding process was identifying four unique intrinsic motivations of designers developing solutions for MC. These motivations are why designers persist with the project despite the constraints and challenges in executing a design process in MC. These four motivations are key aspects that drive the development of a frugal mindset in a designer. Figure 6.9 shows the four intrinsic motivations identified.



Figure 6.9: Intrinsic motivations of a designer developing solutions for the marginal context.

The results of the qualitative research were fruitful in helping understand the frugal mindset and other related aspects. The findings were relatively practical to help the identification of specific strategies for a frugal mindset. The practical nature of the findings can also help in designing supports for imbibing a frugal mindset in novice designers.

The study also highlighted significant similarities between the frugal design guideline (**Appendix A**) and the strategies for a frugal mindset. Similarly, the strategies for

opportunity identification also have significant commonality with the frugal design guidelines. This insight indicates that effectively employing frugal guidelines can help inculcate a frugal mindset in designers. Moreover, since the FDC framework incorporated many frugal design guidelines into the approach, it can be argued that following an FDC framework can help imbibe a frugal mindset.

Still, several of the strategies for a frugal mindset lie outside the scope of any design approach. For example, the strategies of 'Orientation to Accept Ambiguity' and 'Orientation to Sate intellect' cannot be fully addressed through a design process. Thus, explicit steps must be taken to practically apply such strategies during a design project. One way could be to carry out specific design tasks based on the strategies while executing a design project. As discussed earlier, implementing the FDC framework is done through Design Activities that fulfil the objectives of the phases in the framework. Some of these Design activities can also be developed to implement the strategies for a frugal mindset.

For instance, one strategy we found for developing a frugal mindset is 'Orientation to Sate Intellect'. In some of the initial phases of the FDC framework, some Design Activities could encourage designers to evaluate ideas based on how they think it could improve their knowledge and provide creative satisfaction. Ideas that are perceived to provide a high intellectual satisfaction could then be considered further. Such an evaluative process is unusual in a general design process where ideas are typically selected based on performance.

Additionally, the intrinsic mindsets of the designers for undertaking a design project for MC are also agnostic of a design process. However, more research is needed to understand how such intrinsic motivations can be developed in designers. On the other hand, the strategies for opportunity identification can be put into practice more directly.

The study clarified some critical insights we found in our initial literature review. According to experts, designing relevant products for MC involves an in-depth understanding of the context. This aspect was identified as an essential part of imbibing a frugal mindset. Experts also agreed that using a systematic and methodical approach is an important component of frugal design and a technique for nurturing a frugal mindset. Similarly, experts underlined the significance of creating holistic solutions embodied in the "Orientation to holistic solutions" strategy to support the implemental mindset.

6.5 Conclusion

Overall, the study provides important insights into a phenomenon that has received little attention in the current literature. Based on the study's findings, we defined the frugal mindset of designers in a manner that may be examined in future studies. A framework for understanding the frugal mindset was provided in Table 6.1. Furthermore, the study indicates that design tools and supports can be developed to help novice designers adopt a frugal mindset. Implementing frugal mindsets and opportunity identification strategies could also result in better outcomes using the FDC framework. Finally, the identified motivations also open up interesting avenues for future research.

Still, there are some limitations to the study. The exploratory objective of the study favoured a method that focused on depth rather than breadth. For this reason, only a limited number of interviews could be analysed. Although the results from the study were insightful, the small sample makes it hard to say that the identification of frugal mindset strategies had reached saturation. Although studies with similar sample sizes have been published in the field [15], a bigger sample size analysis could still uncover additional relevant strategies.

Most of the subjects interviewed were from India. Although the subject selection can be justified based on the relevance of Indian case studies in the domain [22], geographical belonging may still have some effect on the frugal mindset. However, this study could not uncover any such insights. Similarly, this study could not uncover the effect and importance of experience and educational background on the frugal mindset of designers. Understanding such aspects of the frugal mindset remain as future work in this research.

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Chapter 7 Designing FLOW-A Frugal Design Workflow Toolkit

This chapter is a culmination of the insights and outcomes of the research presented in this thesis.

The research has resulted in two novel frameworks for frugal design in MC presented in Chapter 4. These frameworks were used to develop a toolkit for supporting the systematic and collaborative design of frugal and holistic solutions for marginal contexts (MC). In this chapter, the process of developing the toolkit and the outcomes of its preliminary evaluation are reported.

The first section provides a theoretical background on developing tools. Specifically, a review of analogue tools and 'toolkits' used in design practice is presented. This review enables us to benchmark the selected methodology used in designing the toolkit.

Next, the process used for designing a novel toolkit called '**FLOW – A Frugal Design Workflow Toolkit**' is discussed. The methodology followed an iterative double diamond design process [1] and was grounded on the insights and outcomes of prior work. Section 7.2 discusses the methodology used in designing **the FLOW toolkit**, and Section 7.3 explains its parts and implementation.

Some operational constraints restricted a more extensive validation of the toolkit through workshops and live projects. Due to this, the scope of this research could only consider a preliminary evaluation of the toolkit.

The preliminary evaluation was conducted using a structured questionnaire to understand its usability and "*implementability*"¹. A System Usability Scale (SUS) [2] questionnaire was utilised to understand the perceived usability, and implementability was understood using an adapted 'GuideLine Implementability Appraisal' (GLIA) framework [3]. A detailed discussion of the methodology and outcomes of this preliminary evaluation are presented in Section 7.4.

The chapter concludes with a discussion on the limitations of the preliminary evaluation, the design of the FLOW toolkit, and future work needed for its extensive evaluation.

7.1 Background and Literature Review

The motivation for this research stemmed from the difficulties faced when designing products for the MC. Typical product design approaches and tools were inadequate in supporting a design process in MC that favoured participatory design, collaboration and holistic solutions. In addition, designing frugal solutions was challenging due to specific constraints and a lack of systematic design processes. This lacuna led to the initiation of this thesis work to develop a 'systematic framework' for frugal design and implement it through a design tool.

¹ 'Implementability' is defined as how easy something is to implement in practice.

Chapter 4 presented arguments that developing tools and supports effectively implement theories and insights from design research. Prominent texts in design research also suggest that the central purpose of design research is to develop supports to improve design practice [4]. Therefore, it was important to translate the various research insights and frameworks developed into tools and supports for easier implementation by designers.

Chapters 1 and 2 presented several insights and discussed the importance of design tools for a frugal design process. It was noted that many frugal design guidelines could be implemented through design tools. Moreover, the outcomes indicated that using existing design tools for Co-design, Product-service-systems, Reliability Engineering, and Creative Engineering Design was essential for an effective frugal design process. However, the retrospective analysis of design projects in Chapter 3 found that implementing existing tools without a structured framework was inadequate in supporting a frugal design process.

Chapter 4 also synthesised the FDC and CEH frameworks to operationalise the frugal design guidelines. Strategies for implementing many existing design tools were incorporated in the FDC framework. The chapter also discussed how the frameworks could be translated into design supports for systematically guiding designers working in MC. Developing these frameworks was the starting point of designing a toolkit for frugal design. The first step in developing such a tool was to understand the process of designing a toolkit.

An extant literature review was conducted to understand how design tools and supports can be developed based on known frameworks. This review helped identify a methodology for designing a toolkit and provided insights on the typology of design supports. The review also allowed to establish a benchmark for designing tools and understand the strengths and shortcomings of typical methodologies.

It is important to note for this study that there are slight ambiguities in defining 'design tools' and 'toolkits' [5]. Terms like 'tools', 'toolkits', 'techniques', 'methods', 'methodologies' and 'approaches' have all been used (sometimes incorrectly) to denote different forms of design supports [6]. Sanders et al. [6] define 'design tools' as 'material components' or artefacts that support a specific activity or task in the design process. In contrast, 'design toolkits' are defined as interlinked design tools that serve an overall goal within the design process.

Although Sanders et al.'s [6] classification provide a good starting point for understanding design supports, ambiguities remain in their classification. For example, designers often create 'personas' for understanding typical users. Can 'creating a persona' be considered a tool, technique, or method? The answer is unclear from the distinctions provided by Sanders et al. [6]. To clarify, Peters et al. [10] suggest that 'creating a persona' is not a tool, but a template used to systematically develop a persona can be called a design tool. In light of such known ambiguities, a working definition of the relevant terms is essential for this study.

In this thesis, a tool is understood as design support that assists designers in a single task or activity within the design process. On the other hand, a toolkit is defined as design supports that facilitate multiple design activities and add to a larger goal. For example, a collection of prompts or methods that a designer can interpret in multiple ways can be called a toolkit since it serves multiple objectives. On the other hand, a deck of cards, say with visual or textual prompts for generating new furniture forms, would be considered a tool since its purpose is singular, i.e. generating new forms. Thus, a toolkit can be considered a collection of interlinked, sequentially applicable, or conceptually similar design tools.

7.1.1 Analogue Tools and Toolkits

Another important distinction in design supports can be made as analogue and digital. Analogue design tools and toolkits can be understood as “non-digital” artefacts for supporting design activities that do not use computing devices or internet connections [5]. Analogue toolkits are popular with designers working on collaborative or socio-technically oriented design projects[7]. Some notable examples of analogue toolkits are IDEO human-centred design toolkit [8], IDEO method cards [9], design with intent toolkit [10] and FROG’s Collective action toolkit [11].

Analogue tools and toolkits seem better than their digital counterparts and are preferred by designers during early design phases [12]. They seem to help technical teams generate more empathetic and user-oriented ideas rather than ideas that push certain technologies into solutions [13]. Analogue toolkits are also well suited for the “fuzzy front-end” of the design process due to their ability to handle ambiguity [5], [14]. Such tools and toolkits seem to enable effective and structured thinking when design activities are done in collaboration and physical proximity with other people [15]. Thus, many analogue toolkits are available to support participatory design activities, typically for eliciting responses about the future [16].

Moreover, design teams and participants seem to generate meaningful outcomes despite the ambiguity when using such tools [5], [12]. Analogue tools can also have different purposes, from probing individuals for information, priming participants to generate effective design outcomes, generating a better understanding of contexts, to creating new ideas collaboratively [6]. Dalsgaard [14] discusses the qualities of “perception, conception, externalisation, knowing-through-action, and mediation” are imparted analogue tools in a participatory design setting.

There is also some evidence that the physicality of tools and toolkits aids memory, collaboration and communication between participants in a co-design scenario [17]. Analogue tools specifically designed for individual use, called probes, generate serendipitous and novel user reflections that would otherwise be difficult to extract [18]. Such toolkits can also be used to better understand socio-technical contexts, engage in discussions with the participants, and generate solutions with the people in these contexts [19], [20].

Thus, analogue tools and toolkits are promising support types for design projects that follow participatory and collaborative approaches. Although many general-purpose analogue tools exist (See [21] for a collection of analogue tools), socio-technically oriented design projects, where system-level and holistic solutions are needed, require a collection of compatible and tailored design tools. This requirement has led to the proliferation of design analogue toolkits that serve specific design situations.

For example, the BOP Learning Lab’s ‘Market creation tool-box’ specifically targets developing new markets in MC [22]. Some authors have devised a participatory analogue design toolkit specifically for designing affordable housing projects [23]. There are toolkits specifically for conducting participatory design which children [24]. Similarly, some analogue toolkits focus only on uncovering unsustainable design practices[25]. Peters et. al.[5] present a survey of specialised tools and toolkits that focus on participatory idea generation. The existence of such specialised toolkits suggests that general analogue tools may not be well suited in all design scenarios. As the design contexts, problem domain, and design focus become more specific, new design toolkits must be developed to handle such scenarios.

7.1.2 How Analogue Toolkits are Typically Developed

It was found that the process of designing analogue toolkits for socio-technically oriented design projects is fairly consistent [15], [26]–[30]. In the first step of the process, the problem domain and the specific design scenario are understood, focusing on specific design goals. For example, the focus may be on developing an ideation tool [31], or a toolkit to uncover specific behaviour [25] or, in general, for facilitating a particular type of solution generation [29].

Next, the theories and frameworks developed for these scenarios are translated into design supports through an iterative process [27], [29]. The goal is to develop a physical artefact that operationalises the theories so that non-experts can apply them easily. Often the iterations are done through participatory workshops [27]–[29]. A final step typically consists of finalising and publishing the toolkit for peer review or use by practitioners. Design conferences and workshops were preferred for such presentations [32]. Some authors make such tools freely available online as well [10], [25], [33].

Although the above process of developing design toolkits is rigorous and mostly results in positive outcomes [5], [15], [29], a crucial step is not considered in such methods. Most studies do not sufficiently evaluate the underlying theories on which the toolkits are based [5], [34], [35]. Typically, the underlying theories and frameworks for tools and toolkits are derived from past experiences and assumed to result in positive outcomes without adequate scrutiny. Since the foundations of such toolkits are not evaluated, it becomes difficult to assert that the tools will produce effective results in all design scenarios.

In the approach followed for this research, evaluating the underlying frameworks for frugal design (the FDC and CEH frameworks) was the first critical step in ensuring the final toolkit's effectiveness. Evaluating the frameworks provided an empirical grounding and the necessary theoretical validation for subsequent tool development.

Moreover, the FDC and CEH frameworks were practically implemented in an abridged version during the design conceptualisation exercise. In Chapter 5, the FDC-test workbook can be considered a prototype or the first iteration of a design tool that operationalises the FDC framework. Therefore, the results reported in Chapter 5 indicate that the 'prototype design tool' produced positive results. Consequently, it provides significant confidence that a more elaborate design toolkit based on the proposed frameworks can also produce satisfactory results.

Based on the arguments above, the *overall methodology* followed in this study for designing an analogue toolkit for systematic frugal design can be considered as:

- 1 **Identification of lacuna** for a design tool through extant literature review.
- 2 **Analysis of professional experience** and projects to develop frameworks for tool development
- 3 **Development of foundational frameworks** for designing tools and toolkits.
- 4 **Empirical evaluation of foundational frameworks** to understand their effectiveness and for theoretical validation.
- 5 **Synthesis of design toolkit** based on the proposed frameworks
- 6 **Preliminary evaluation** of the design toolkit

Chapters 1 through 5 discussed the work related to the first three steps of the overall methodology. In the following sections, the synthesis of the design toolkit, the methodology followed, and its various parts are discussed in detail.

7.2 Synthesis of the toolkit

The double diamond model [1] proposed by the British Design Council was adapted for synthesising the frugal design toolkit in this research. This versatile approach has been widely adopted for designing products [36], systems [37], services [38] and also design tools [39], [40].

Following a double diamond model, a typical design process starts with a ‘divergent’ primary and secondary research phase. This research phase helps outline design insights and opportunities, which are then synthesised into a design brief in a ‘convergent’ manner. In the next ‘divergent’ phase, multiple design ideas are generated, followed by a ‘convergent’ idea selection process, ending in the final solution. The two divergent-convergent phases are represented as two ‘diamonds’ giving the model its name.

Figure 7.1 shows the double diamond model overlaid with the steps followed in this study for synthesising the toolkit. Outcomes of each convergent-divergent phase are explained in the next two sub-sections.

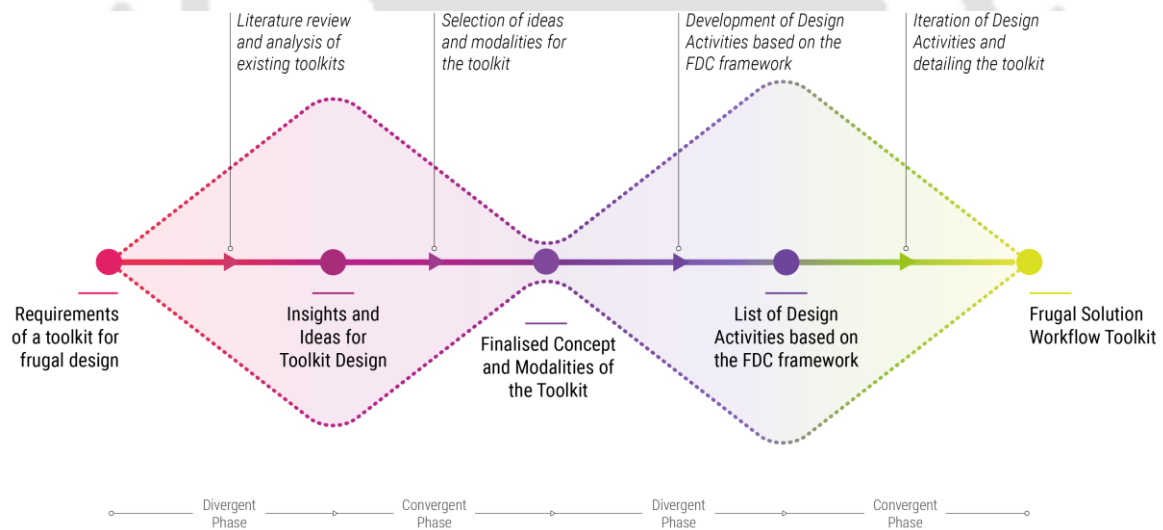


Figure 7.1: The process followed for designing the toolkit based on the double diamond design model [1].

7.2.1 First Divergent-Convergent Cycle

The first convergent-divergent cycle started with reviewing existing analogue toolkits to identify the modalities and forms in which toolkits are currently available. The results of the divergent phase were a list of ideas for the toolkit. Next, the ideas were evaluated and selected in a convergent phase using the insight from the literature review. The phase ended with a finalised concept for the toolkit.

Some of the notable examples of toolkits analysed in this phase are shown in figures 7.2 to 7.7. In addition, insights were drawn from the comprehensive reviews of analogue tools by Peters et al. [5], Wölfel & Merritt [34] and Stappers et al. [41]. Most of the toolkits analysed were largely based on designers' professional experience, where the underlying theories and foundations were not adequately elaborated. Peters et al. [5] made a similar observation with many analogue design tools in their comprehensive review.



Figure 7.2: IDEO human-centred design toolkit. [8]



Figure 7.3: IDEO method cards [9]



Figure 7.4: Design with intent toolkit [10]



Figure 7.5: FROG Designs' Collective action toolkit [11]



Figure 7.6: BOP Learning Lab's 'Market Creation Toolbox' [22]



Figure 7.7: Paco Collective's Design for change in marginalized communities toolbox [60]

A few key modalities were identified in the analysis. Most toolkits were presented as booklets, cards, posters or digital files. Some inherent benefits and limitations in each modality were noticed in this review.

Toolkits which are presented in the form of booklets could provide significant details to the practitioner for implementing its various parts (e.g. HCD and Creative action toolkits [8], [11]).

Such toolkits contained some important theoretical information on the foundations of the toolkit. However, a shortcoming was that they presented information linearly and sequentially, potentially reducing the flexibility in implementing the toolkit. Moreover, a booklet reduced the possibility of quickly referencing important concepts in a toolkit.

Another prominent modality that fills the gaps of booklets is using 'Cards', which offer more flexibility since the sequence of the contents was unimportant [34]. However, cards are only suitable when the information to be provided is succinct and relatively abstract. For example, Cards work well for design prompts and as quick references (see Design for Intent [10] and IDEO method Cards [9]).

Some toolkits contained posters and canvases [42], [43], which were beneficial for supporting collaborative design activities. Posters and canvases are structured templates where individuals or multiple participants can record relevant information during design activities. This information can then be analysed to derive design insights. As evident, posters and canvases work better than booklets and cards for collaborative design activities. However, there is little scope for providing relevant information and theories to effectively direct or facilitate such activities. Toolkits that focused on posters and canvases were mostly digital files since participants require multiple copies of a canvas when executing design tasks collaboratively (e.g. servicedesigntoolkit.org [43])

After reviewing the different modalities, several overall ideas for the toolkit were generated. Ideation was based on the compatibility of the different modalities with the FDC framework. Additionally, the FDC-test workbook was extensively used for directing the idea generation process.

In addition to the requirements outlined in Chapter 3, the ideation exercise itself reinforced some crucial requirements for the toolkit. A toolkit for frugal design needs to provide adequate foundational information to practitioners, must be flexible to handle projects of varying complexities and provide scope for collaborative design. Therefore, a concept was chosen that combined a booklet, cards and canvases. The booklet could provide foundational and comprehensive information on a systematic frugal design approach. The cards could be used to select and plan relevant design activities to enhance flexibility. Moreover, the canvases could facilitate collaborative design activities at crucial points in the design process.

The finalisation of the toolkit's overall concept completed the first divergent-convergent phase in the double diamond approach. In the next divergent step, the toolkit was detailed based on the FDC framework.

7.2.2 Second Divergent-Convergent Cycle

Next, these Design Activities were iteratively refined, and the final toolkit was detailed in a convergent manner.

Chapter 4 discussed the FDC framework and its implementation by developing 'Design Activities'. These Design Activities are specific outcome-oriented tasks that fulfil the overall goals and objectives of various sub-phases of the FDC framework (See Table 4.2). In the divergent phase of the second cycle, a list of Design Activities based on the FDC framework was created.

This list was iteratively developed considering a medium to high complexity design project. The analysis of existing case studies Chapter 2 resulted in focus areas for projects of different types. Solutions with multiple such focus areas can be considered more complex for development. Additionally, Chapter 2 also presented criteria to assess the complexity of a frugal design project. These results outlined that the 'Design Activities' needed for a higher complexity design project would encompass the activities needed in a typical low complexity project. Therefore, the focus at this divergent stage was to develop a granular and comprehensive list of Design Activities to ensure that the objectives and goals of the FDC framework were adequately met for projects of all complexity levels.

Additionally, Design Activities were developed considering three user archetypes. These archetypes resulted from assessing the backgrounds and work practices of experts interviewed during the study on Frugal Mindset (See Table 6.2). The first archetype was a design team that works within an organisation on a structured design brief (e.g. Rishiraj, Aditi and Fabio). In this scenario, the activities should be suitable considering the organisation's existing resources and work with existing product development processes. The second user archetype is the design team working within a design consultancy (e.g. Sudhir, Sateesh and Rishabh). Activities were developed considering the limited resources in the scenario but higher independence in project execution and increased scope for collaboration with external agencies. The third archetype considered academicians and design students (e.g. Dr Dipankar). For this user type, the focus was on developing activities to guide a systematic design process in MC and create a scope for future research.

Creating a comprehensive list of Design Activities enabled the integration of research insights, frugal design guidelines, and aspects of the frugal mindset outlined in prior chapters. In the first iteration, a list of 186 Design Activities was created for various FDC framework phases considering the project complexity and multiple user archetypes. In the next convergent steps, the list of Design Activities was revised and iterated three more times through affinity mapping [44].

The second, third and fourth iterations of creating Design Activities focused on reducing the overall number of activities and improving their suitability for low and medium complexity projects. Similar Design Activities were combined and subsumed into others to reduce the number of activities. The second iteration reduced the number of Design Activities to 49, the third to 39 and finally, a list of 28 Design Activities were selected for the final frugal design toolkit.

Additionally, information about the Design Activities relevant to toolkit design was detailed with each iteration. In the second iteration, each activity was detailed with a description, recommended steps and the nature of work needed (e.g. fieldwork, interviews, co-design, prototyping, analysis, synthesis). The third iteration defined the expected outcomes, estimated time needed, existing tools and strategies for a frugal mindset needed to support each Design Activity. The third iteration also focused on creating specific canvases and posters to facilitate participatory design in various activities.

In the final iteration, the Design Activities were further refined to improve practical application after discussion and review with experts. Most importantly, multiple Tools, Templates, Prompts, and Probes were developed to support the Design Activities.

Appendix K lists the various Design Activities considered in the final frugal design toolkit and the canvases designed for each activity.

Finally, a visual language for the toolkit and a prototype was developed during this iteration, as shown in Figure 7.8. The prototype was then evaluated for quality and adherence to the research insights.



Figure 7.8: A prototype of the FLOW toolkit showing the FLOW workbook and the FLOW Cards.

The toolkit was named **FLOW - the Frugal Design Workflow Toolkit**. Appendix L shows some images of the final toolkit.

7.3 FLOW toolkit Explained

The complete FLOW Toolkit can be accessed from the link²: <https://qrgo.page.link/CODpK>

When synthesising the toolkit, the goals were mainly to operationalise the FDC framework and incorporate the major insights from the research. The outcomes of Chapters 1 and 2 were used as guides for creating the Design Activities and various tools. The requirements identified in Chapter 3 were referred to for organising the toolkit's activities. Finally, the frugal mindset strategies were interpreted and incorporated in each design activity listed in the FLOW toolkit.

The toolkit also aimed to include participatory approaches in as many Design Activities as possible besides the four key co-design sessions outlined in the requirements in Chapter 3. It incorporated existing processes, tools, methods, and novel design tools based on the various insights from this research.

These Design Activities, Insights, and tools were then woven together to develop a comprehensive, easy-to-understand, and practically applicable 'workflow' that enables a designer to systematically develop frugal and holistic design solutions for MC.

FLOW toolkit was executed as three separate components: the **FLOW workbook**, a set of **FLOW cards** and the **FLOW posters**. The FLOW workbook is a booklet and the main component of the toolkit. It describes various Design Activities, processes, steps and tools required for conceptualising holistic and frugal solutions for MC. FLOW Cards provide abridged information

² The link leads to a cloud storage provider (Google Drive). Any warnings can be safely ignored.

on Design Activities in the workbook and work as a ‘creative planning’ and quick reference tool for the project. The FLOW Posters are designed to track crucial information during a project and focus the design effort. Apart from these, the workbook contains several **FLOW Canvases**, which function as tools, probes, prompts, and templates that help execute the Design Activities effectively. Each of the components is explained below.

7.3.1 FLOW Workbook

The FLOW workbook is divided into five sections and contains the theoretical foundations of the toolkit, a list of Design Activities and the FLOW Canvases. The first section serves as an introduction and contains the theory and background needed to apply the toolkit in practice. The remaining four sections correspond to each of the four phases of the FDC framework. These last four sections provide comprehensive explanations of each Design Activity identified during toolkit synthesis. Each Design Activity is described in a layout spreading of two pages in the workbook, as shown in Figure 7.9.

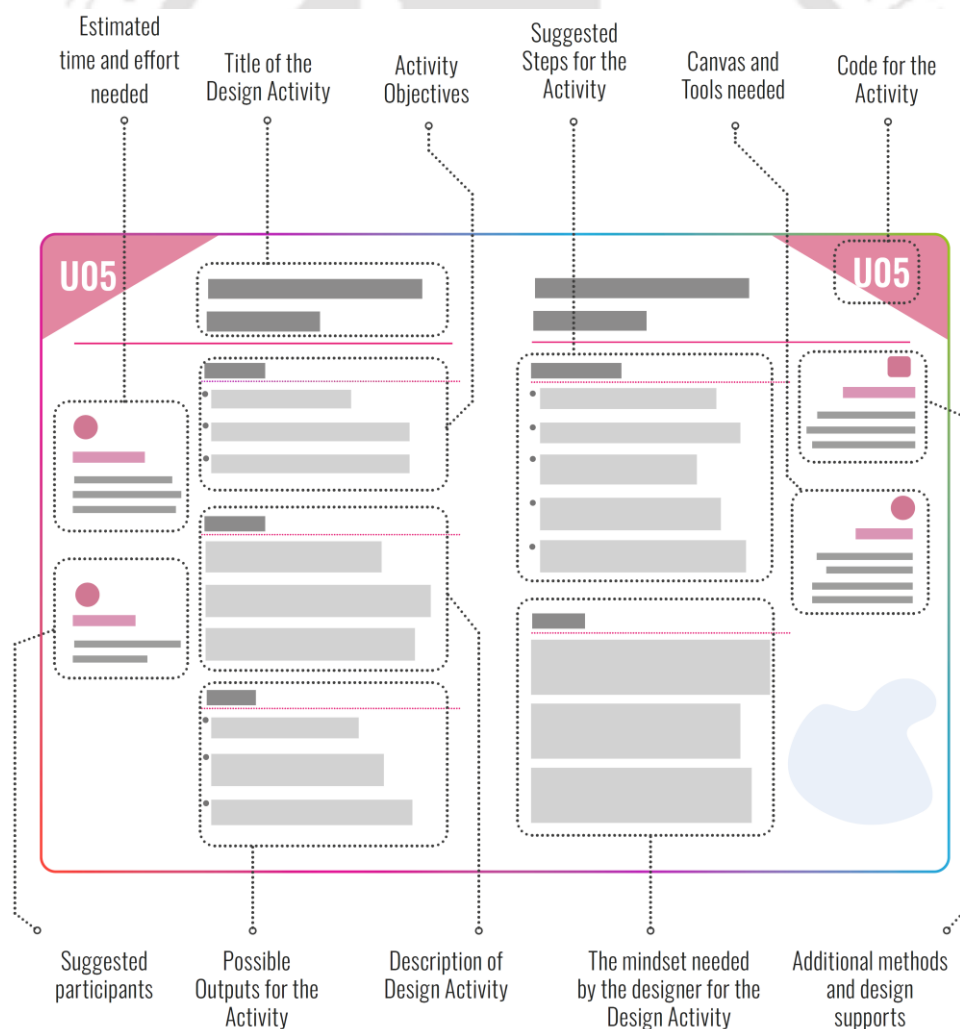


Figure 7.9: Schematic and layout of a two-page spread explaining a Design Activity in the FLOW workbook.

The page spread contains information for effective execution of the Design Activity and other necessary information.

First, a code is given to each stage for easy cross-referencing, and a short title provides a glimpse of the activity. The objectives, description and suggested steps for executing the activity is shown in the body text. Finally, a short discussion on the mindset needed for executing each design activity is shown. The strategies of frugal mindset identified in Chapter 6 were used for creating specific instructions and suggestions noted in the 'Mindset 'section.

Apart from these details, short descriptions along the page margins provide additional information for the activity. An estimation of time and effort needed for executing the Design Activity in a medium complexity project is illustrated.

The insights from Chapters 2 and 3 indicated that project complexity in a frugal design project for MC results from constraints in the context and the ambiguities in the holistic aspects of a solution. Therefore, the comprehensive list of Design Activities created during the synthesis of the FLOW toolkit considered three levels of project complexities: low, medium and high. The design ambiguities of a low complexity project primarily revolve around the product's design and embodiment. A medium complexity project may contain ambiguity regarding one or more aspects of the business model, service design, dissemination, and product embodiment. Finally, a high complexity project is ambiguous, considering all the elements of a solution proposal.

Therefore, a tool was developed to estimate the project complexity based on the insights from Chapters 2 and 3. The tool is implemented as a canvas in one of the initial design activities in the workbook (pg. 54 in FLOW workbook or **Appendix L**). A designer can use this canvas during project planning and select or modify the Design Activities as needed.

Another section on the margins discusses the participants with whom the activity can be collaboratively done. Chapter 3 noted the different stakeholder types necessary for a frugal design project other than the users and promoters. It was found that design research in MC needs crucial inputs from visionaries in the context and people who will be part of the solution's value chain. Thus, each Design Activity was analysed to understand the appropriate stakeholders who can contribute to it and recorded in this section.

The tools and resources needed for executing the activity are mentioned in the right-hand margins. Relevant existing design tools were identified from prominent books related to product development [45], collaborative design [46], engineering design[47], service design[48], [49] and design research [50], [51]. Apart from existing tools, the section also mentions the specific FLOW Canvases and resources that help execute the Design Activities.

7.3.2 FLOW Canvases

Most of the Design activities in the FLOW workbook have accompanying ‘Canvases’. Figure 7.10 shows the template and structure in which the FLOW Canvases are presented in the workbook. The Canvases serve as **probes, prompts, templates, and tools** for effectively executing the Design Activities.

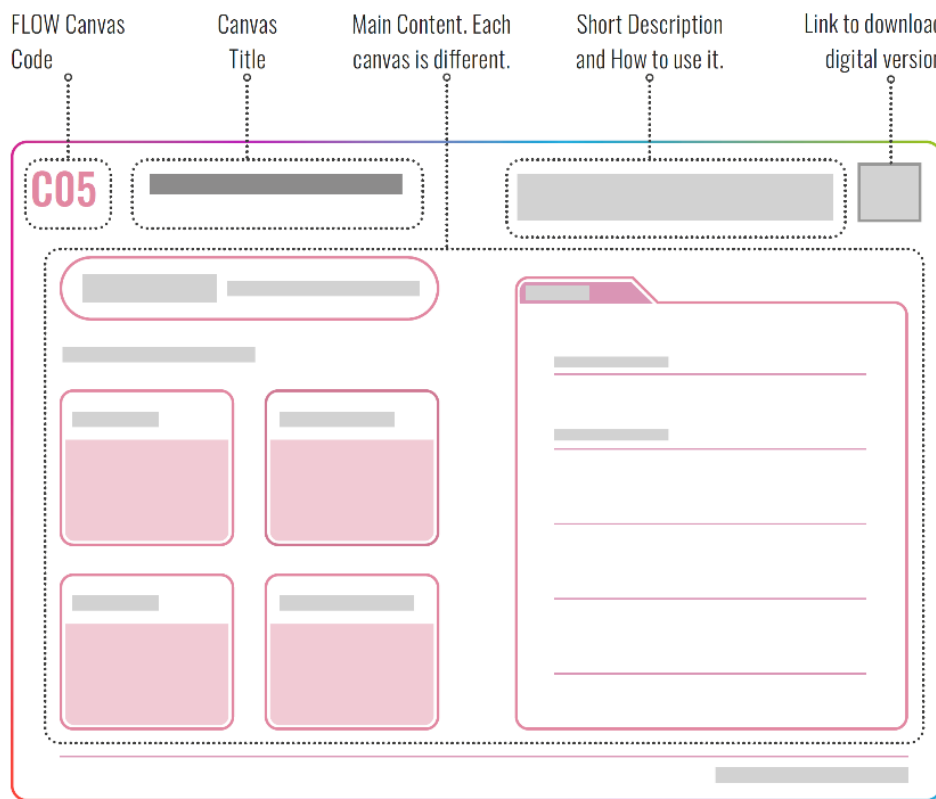


Figure 7.10: The structure and layout of a FLOW Canvas presented in the toolkit.

Probes are tools typically used by an individual designer to “reflect on and express their experiences, feelings and attitudes” for identifying relevant information and inspiration [16]. The Design Activities which focus on reflective thinking and creating the right mindset for frugal design are supported using probes. For example, Canvas C01 and C02 are used to create the project’s mission and goals. In these canvases, the designer reflects on the personal motivations and expectations of the project promoters to arrive at meaningful project goals and then discuss the outcomes in a participatory session.

Prompts are design tools that provide specific, succinct and abstract information which nudge a designer to execute certain tasks or think in a certain manner. Prompts work by restricting the designer’s solutions space and directing them towards certain solution types [52]. The Design Activities where specific information, guidelines and insights while generating solutions are accompanied by prompt-based canvases. For example, the Canvas C12 is based on the CEH framework and helps identify contextual constraints and mitigation strategies. Similarly, Canvases

C19, C20 and C21 are prompts that nudge a designer to consider several frugal design guidelines when developing the product embodiment and system components.

Templates are canvases that provide a structured way to record important data during an activity or participatory session. Such information may emerge from the analysis of certain information or be observed during analysis. For example, Canvas C13 and C18 are templates to record design ideas and contain spaces for drawing and noting relevant details. On the other hand, Canvas C15 and C24 are templates that provide a structure to develop technical reports based on previously conducted analyses.

Many of the templates in the toolkit are specifically designed to support co-design activities, reach consensus and make decisions. For example, Canvas C03 can be used to collaboratively develop mission statements for the project. Similarly, Canvas C13 can be filled up individually by a designer and then its outcomes collaboratively reviewed to generate an overall design direction.

Several canvases directly incorporate the insight and findings from this thesis. For example, Canvas C08 and C11 use the CEH framework to direct the stakeholder interviews and analyse users' daily lives. Canvas C19, C21 and C22 use the frugal design guidelines, strategies for creating solution proposals and insights from the literature review as design prompts. Canvas C04 for evaluating the project complexity directly resulted from the insights from chapter 3. Similarly, Canvases C14 for recording design ideas, C17 for analysing existing solutions and C23 for creating stakeholder configuration maps were adapted from the steps in the FDC-test workbook.

Canvases were designed to be solution-agnostic and can be creatively interpreted based on project objectives. Designers can modify certain canvases to support participatory activities and even use them when solutions are not necessarily product oriented. Thus, FLOW canvases provide starting points for designers to develop customised tools and collaterals for co-design when developing frugal solutions for MC.

7.3.3 FLOW Cards

FLOW Cards were designed to improve the flexibility of the toolkit and allow for ‘creative planning’ of the project. Each card references a Design Activity page found in the FLOW workbook and contains abridged information on its implementation. FLOW cards can be used for quick reference when planning the design project. Figure 7.11 shows the schematics of the FLOW Cards.

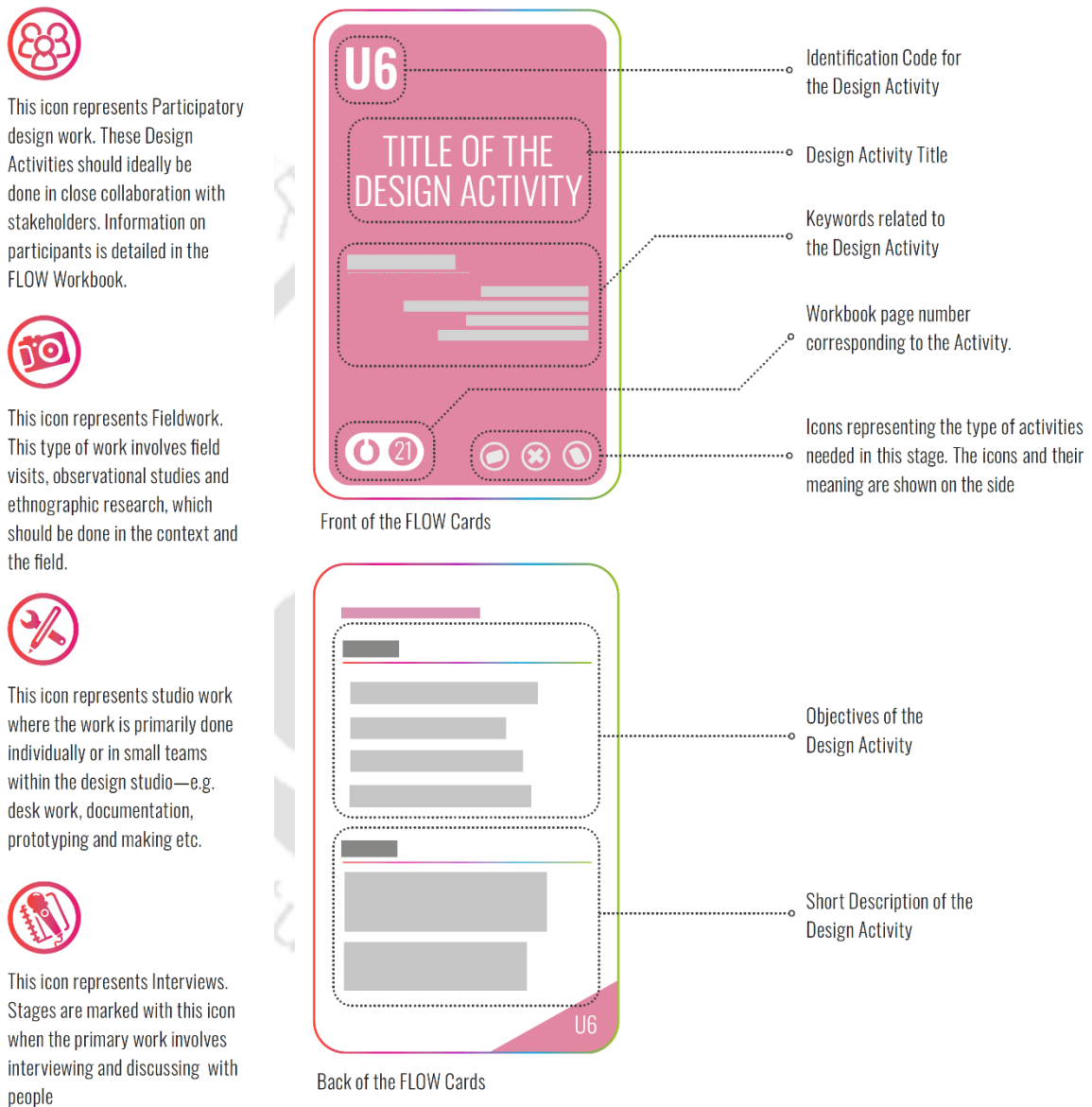


Figure 7.11: Schematic and Layout of the FLOW Cards.

Each FLOW card contains the title of the Design Activity, its objectives, some relevant keywords and a short description. The front of the cards shows the page number referencing the FLOW workbook where the activity is listed. In addition, each card shows one or more icons seen in Figure 7.11 to designate the type of work needed. The four icons represent participatory work, Fieldwork, Studio work and Interviews. It was found that the Design Activities needed one or

more of these types of work to complete its objectives. Having these icons nudge designers to consider these different types of work when executing the process.

For example, the Design Activity 'U6-Understand the daily lives of users' (See Figure 7.12 and pg. 76 of the FLOW workbook) requires designers to conduct field visits, observational studies, interview stakeholders, and participatory exercises to fully understand the user's daily lives.

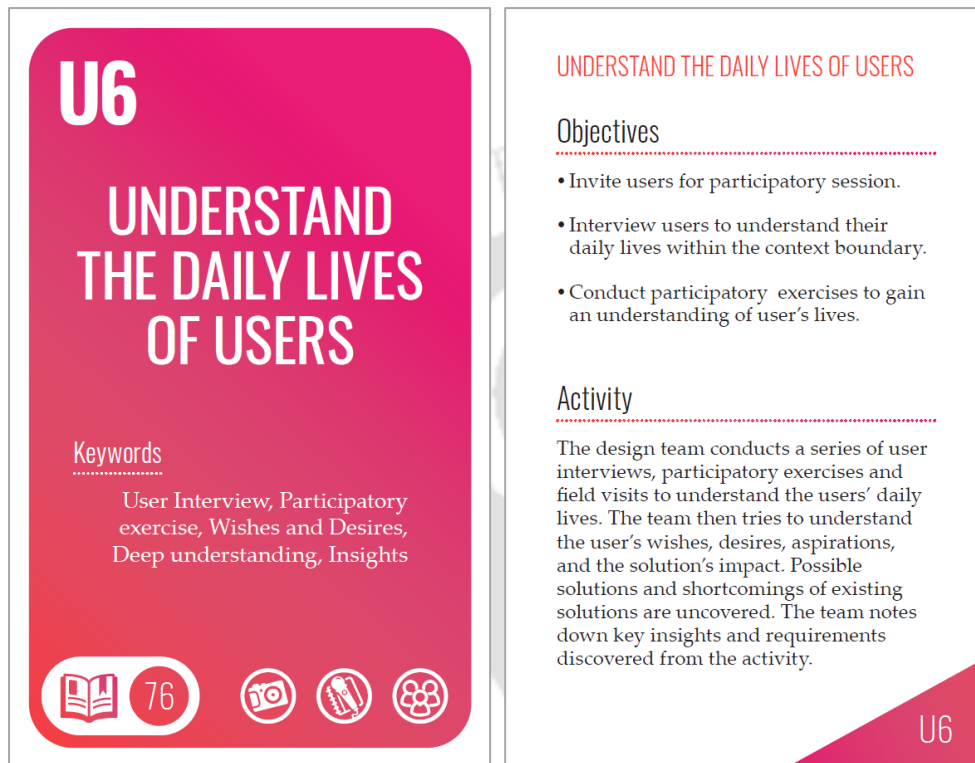


Figure 7.12: The two sides of one of the FLOW Cards.

FLOW cards were primarily designed for use during the initial phases of a frugal design process. Every Design Activity in the FLOW toolkit need not be executed for every design project. A designer is expected to tailor the frugal design process and select relevant activities based on the project complexity, scope and goals.

For example, some of the Design Activities related to the systems-level design can be combined for low-complexity projects. Similarly, for higher complexity projects, the activities related to product embodiment may need to be elaborated if significant R&D is needed for technology development. This aspect of the FLOW toolkit makes it flexible for use in different types of projects.

Thus, The FLOW Cards provide a summary version of the FLOW workbook, thereby reducing the planning efforts in early design phases. The designer can use the cards in an affinity mapping exercise to select the relevant activities and plan the project's flow. The cards let designers rearrange the sequence of Design Activities differently than the one suggested in the workbook. This process is termed as 'creative planning'. After the project planning is done, the FLOW Cards work as a ready reference for the designer.

7.3.4 FLOW Posters

FLOW posters perform similarly to mood boards [51] and are designed to remind designers of crucial information and milestones as the solution is developed. Unlike canvases, posters are temporally dynamic, where the insights from multiple Design Activities are recorded in a single poster as they are completed. Thus, the posters work as sources of information and inspiration during the project execution.

The FLOW toolkit includes four A1 sized posters, each designed to capture and display specific information utilised throughout the design process. The posters are meant to be displayed in the design team’s working space and filled with relevant information as the project progresses. The four posters in the toolkit are illustrated in figure 7.13 and 7.14

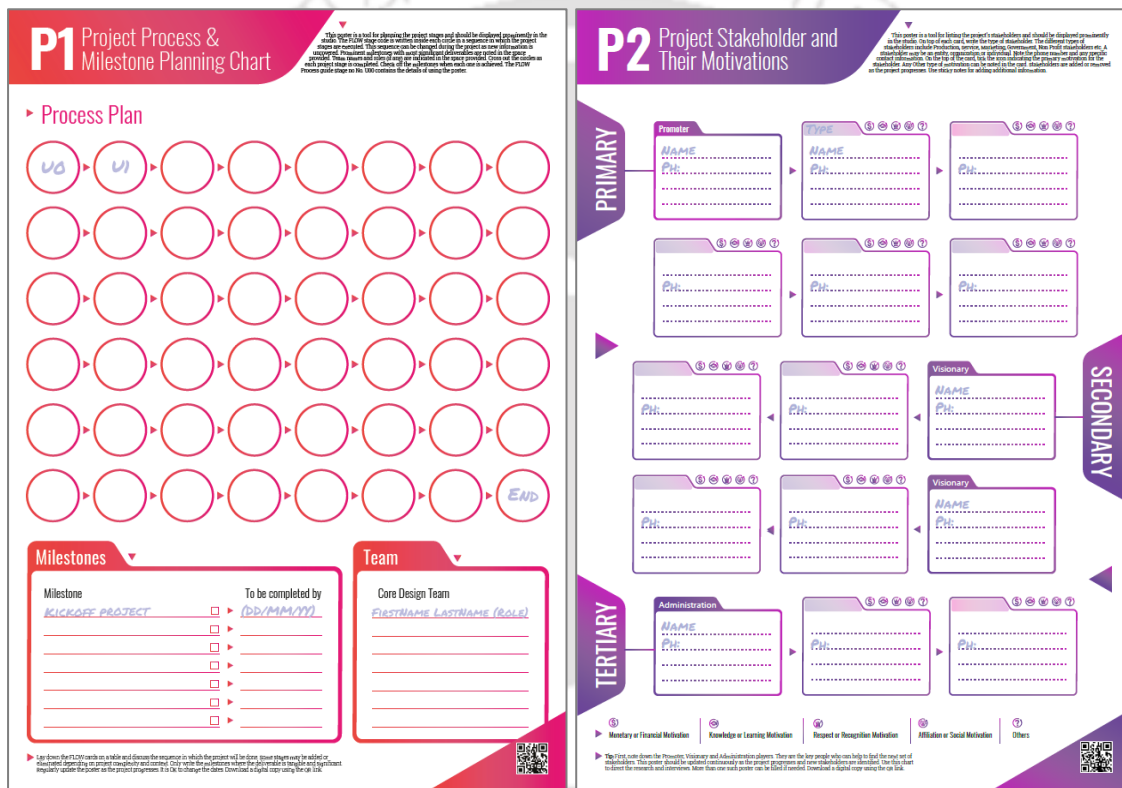


Figure 7.13: FLOW Posters P1 and P2. Poster P1 is for recording the project process and milestones; Poster P2 is for recording the project’s stakeholders;

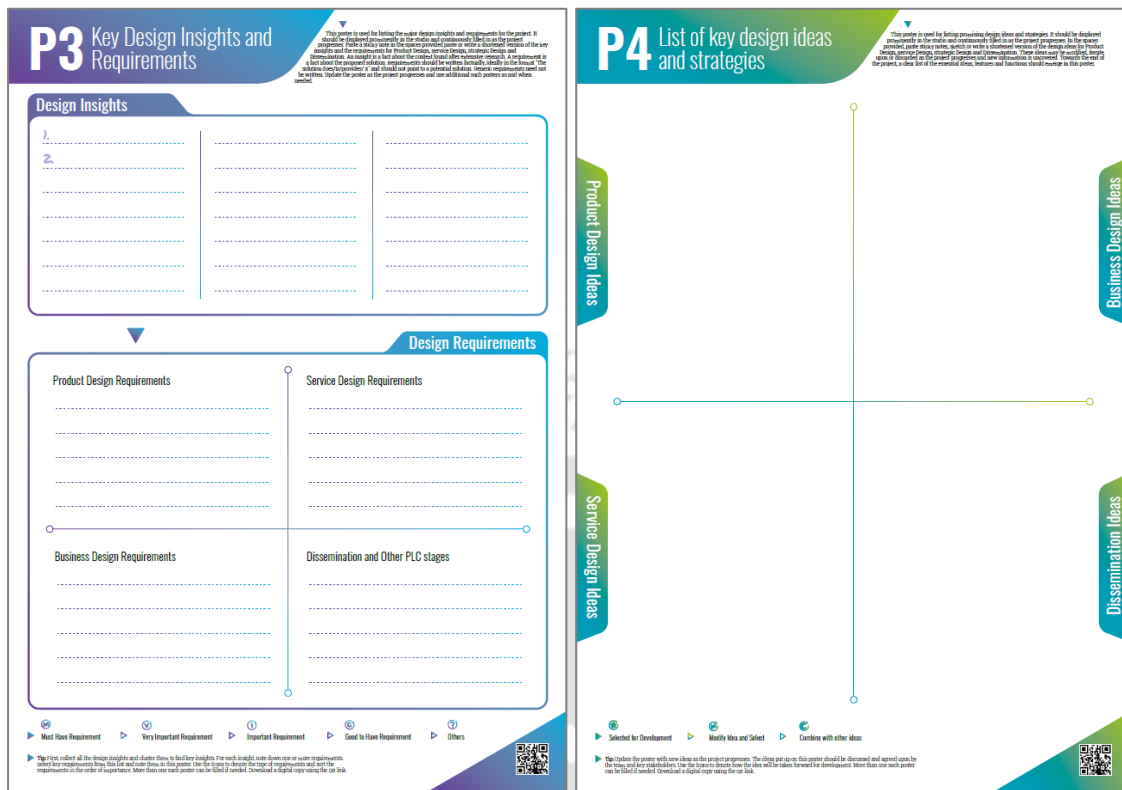


Figure 7.14: FLOW posters P3 and P4. Poster P3 records key design insights and requirements, and Poster P4 lists the design ideas and insights.

The first FLOW poster (P1) showcases the project plan. The sequence of Design Activities and the significant project milestones are recorded in this poster. Poster P1 is updated as the project progresses and milestones are achieved. As plans change and new information is uncovered during the project, the poster can be updated to reflect the new plan and milestones, thus providing clear communication within the design team.

The second poster (P2) lists stakeholders, visionaries, agencies and influential persons with a stake in the solution or could support its development. As the project progresses, additional stakeholders can be listed by making multiple copies of the poster.

The third poster (P3) lists critical design requirements and insights. Once a certain amount of work is completed, designers can use P3 to define the key requirements and insights for the solution. Poster P3 then serves as a reminder to focus the development efforts towards meeting these requirements. The poster can also act as a changelog if it is continuously updated.

Finally, the fourth poster (P4) lists the most crucial design insights and ideas that direct the conceptualisation process. This poster is also updated as the project progresses, and more ideas are generated during research analysis, product prototyping and evaluations.

Specific Design Activities in the FLOW workbook specify when each poster can be updated. As the project progresses, designers can consult the posters for specific information, focus on the appropriate design direction and even use it as prompts for idea generation. The posters thus provide the design team with a clear and visible goal when working individually or during co-

design sessions. The four posters are accessible as digital downloads, allowing multiple copies to be utilised as needed during the design process.

7.3.5 Implementing the FLOW Toolkit

The FLOW Toolkit was designed as a comprehensive implementation of the FDC framework, but it can also *add* to the existing development processes. Designers can use FLOW to develop a project plan compatible with existing product development frameworks in their organisations. The toolkit allows careful considerations of the project complexity, time frame available, and resources at hand when planning the project, thus supporting a frugal mindset. Overall the FLOW toolkit can help in the effective and systematic execution of a frugal design process. However, there are some considerations to implementing the toolkit effectively.

Firstly, the formation of the design team remains out of the scope of the Design Activities in the toolkit. Secondly, the implementation of the FLOW toolkit must start with an initial project brief and agreements between the initiators and designers. This initial design brief is the starting point of the toolkit.

Finally, and most importantly, a preliminary field visit and assessment of the design brief is recommended before implementing the FLOW toolkit. Such work is necessary to understand the project's scope and if the toolkit fits the project. This work is accommodated as the first Design Activity in the toolkit (U0) and recommends designers to identify persons, locations, organisations, and other entities of interest. Based on the initial brief and the field visit, a decision for implementing the toolkit should be taken.

Once the decision of implementing the toolkit is made, the first step is to review the FLOW workbook, cards and posters. The toolkit incorporates specific research insights from the Design Activity 'U1-Create a project plan' onwards. When executing U1, the applicability of each Design Activity for the project is assessed. Designers are recommended to use the FLOW cards to select the relevant activities for the project based on the scope, project complexity and resources at hand. If project complexities evolve, the plan could be updated, and some previously excluded Design Activities may be reconsidered. Furthermore, designers must attempt to form a sequence in which the activities are executed and use affinity mapping methods to combine and expand activities to form the final project plan.

If the FLOW toolkit is unsuitable for a project, it can still benefit some specific design tasks. Designers can review the various Design Activities and FLOW Canvases and select a few to enrich their preferred design approaches. Furthermore, many of the canvases provide prompts and templates to support co-design activities which can be used outside the structure of the FLOW toolkit.

It is important to note that the suggested steps and outcomes of the Design Activities mentioned in the workbook are indicative and can be altered as per the project requirements. Similarly, the workbook directs the designers to seek out additional information and tools wherever applicable, making it flexible in implementation. An important note is that the FLOW toolkit cannot support the creative conceptualisation of frugal solutions. The creative aspects of the design remain the strengths of designers implementing the toolkit.

Finally, the current version of the tool is not entirely applicable to intangible outcomes, such as social innovation, media, or visual communication solutions. The FLOW toolkit is most suitable when the final solution is envisioned as a physical artefact (e.g. a product). Still, many Design Activities and Canvases can be adapted for such projects.

With the design of the FLOW toolkit complete, it was important to understand if designers would consider using it in their practice. Therefore, a survey was conducted to assess the toolkit's overall usability and 'implementability'. The outcomes of this survey are discussed in the section below.

7.4 Preliminary Evaluation of FLOW

Most authors reported a qualitative validation of design tools through iterative workshops [5], [41]. Analysis of outcomes and interviews from these workshops are used to estimate the toolkit's validity. The toolkit can be continuously iterated with multiple such workshops until a satisfactory version is created. Hoolohan and Browne [28], for example, describe a participatory and iterative approach used for designing their tool. The methodology has similarities with the Grounded theory approach [53], thus sharing some of its limitations as well (See Byrant and Charmaz [54] for a comprehensive review of the theory).

In contrast, quantitative evaluations may provide a better assessment of a design tool but are limited by the measurement methods. For example, the setup for quantitative evaluation of a tool requires a controlled design setting where the tool is implemented. Such design scenarios may not accurately reflect the actual design contexts in which a tool is later implemented.

Quasi-experimental setups have also been used for evaluating design supports [55]. In our case, a quasi-experimental study indicated that better outcomes could be derived using the FDC framework. Therefore, the experimental study provided some validation for the effectiveness of the FLOW toolkit.

Nonetheless, a mixed-method approach that includes quantitative techniques (to assess the underlying theories) and qualitative assessments (to understand effectiveness in actual design projects) is ideal for validating design supports. However, as Blessing and Chakrabarti [4] point out, such a process is time and resource-intensive, and it may be beyond the scope of a single PhD research project. Thus, only a preliminary evaluation of the FLOW toolkit could be undertaken as part of this thesis work.

This preliminary evaluation aimed to understand the FLOW toolkit's ease of use, 'implementability' and usability. Understanding these factors can indicate if designers will be interested in using the toolkit for their design projects. An online survey with a structured questionnaire was chosen for the evaluation due to the potential to access a larger sample size.

7.4.1 Methodology

To understand the toolkit's 'implementability', a questionnaire was designed based on the GLIA framework [3]. In clinical research, Implementability is understood as the characteristics that

predict the ease of using certain medical guidelines [56]. Several instruments have been designed to measure the ease of use of such guidelines in practice [3], [57]. Although such instruments have not been typically used in design research to the best of our knowledge, the underlying frameworks could be still adapted for the evaluation.

“GuideLine Implementability Assessment (GLIA)” framework provides a set of characteristics that constitute the construct of ‘implementability’ [3]. These characteristics were adapted for developing a set of survey questions without straying too far from the original definition.

Appendix M shows the final questionnaire with the GLIA framework characteristics mentioned in the second column of Table M.1.

Another goal in the preliminary evaluation was to understand the usability of the FLOW toolkit. The System Usability Scale (SUS) questionnaire [58] provided a good starting point for this purpose. The SUS questionnaire contains ten questions based on whose answer a usability score can be calculated to accurately represent system usability [58]. Since SUS is system-agnostic [59], its questions are generalisable and easier to adapt for this evaluation. Additionally, the brevity of the questionnaire (it contains only ten questions) made it suitable for the study.

The SUS questionnaire is answered on a Likert scale with verbal endpoints of 1=Strongly Disagree to 5=Strongly agree. The usability score from the evaluation is calculated using the equation below:

$$SUS\ Score = \left(\sum (Answer\ to\ Odd\ questions - 1) + \sum (5 - Answer\ to\ Even\ questions) \right) * 2.5$$

As a thumb rule, a SUS score of above 70 indicates an acceptable level of usability, whereas better usability is indicated by as sore in the 80 to 90 range [58]. It has been cautioned that the scores obtained in each question individually are not meaningful [2], and only the final score derived from the SUS questionnaire must be used to make judgements. However, knowing the responses to individual questions can help understand the constituents that lead to the usability score [58].

The questionnaire was administered online to a total of 140 subjects. The selection of subjects was done through a combination of non-probability sampling methods. Professional contacts of authors were contacted for participating in the survey, who were then asked to refer it to their networks. Additionally, students and faculty at acquainted academic institutions were sent the survey and requested to forward it to other academicians, design students and professionals. Responses were filtered using the background and experience in designing for the MC. Subjects could only answer the questionnaire if they had completed at least one project related to the MC and were from a relevant background. After filtering, responses from 74 respondents were qualitatively analysed and interpreted for generating insights.

7.4.2 Results of the Preliminary Evaluation

The responses were filtered based on the respondents’ backgrounds and involvement in MC design projects. The assumption was that respondents who had prior experience designing for MC could better assess the toolkit’s usability. Also, since respondents had not used the toolkit in a project before attempting the questionnaire, the prior experience provided a basis of reflection and helped them answer the questions. Figure 7.15 shows the distribution of total respondents who attempted the questionnaire (140) and their prior experience.

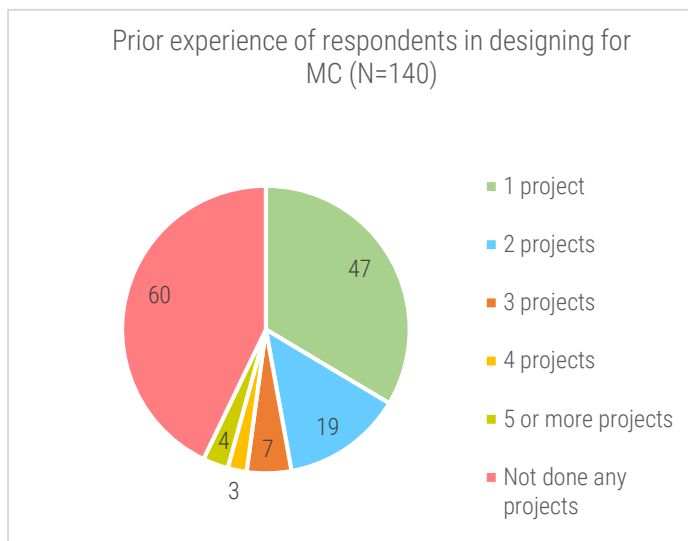


Figure 7.16: Number of survey respondents

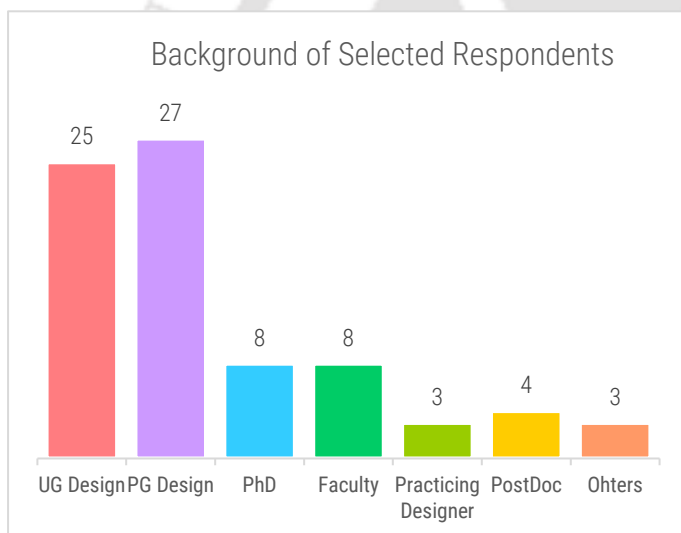


Figure 7.15: Number of selected respondents and their background

A total of 74 responses were obtained after filtering the respondents who had been part of at least one design project for MC. The background of the selected respondents is shown in Figure 7.16. The majority of the respondents (67%) were design students at the undergraduate and postgraduate levels. Although this restricts the overall generalizability of results, the perspective of novice designers can be understood based on the survey. Moreover, Understanding the perception of usability in novice designers is important since they are the ones who stand to benefit the most from the FLOW toolkit.

Survey respondents were primarily from Asia (82%, n=61), with some more responses received from Europe (10%, n=7), South America (7%, n=5) and one from Central America. Therefore, results should be considered primarily as views of designers from Asia, most of whom probably belong from India due to the sampling strategy employed.

7.4.2.1 Usability of the toolkit

The first step in the evaluation was to calculate the SUS Score of the FLOW toolkit using equation 7.1. The **average SUS score for the 74 selected responses was 70.6 (s=13.7)**. Based on

the outcomes, the overall usability of the FLOW toolkit needs some improvement.

The Average SUS scores for each group of respondents were also calculated and shown in Figure 7.17. It can be seen that the average SUS score is fairly consistent across groups, except for practising designers and post-doctoral researchers. The three practising designers felt that the usability of the toolkit was more (SUS=83.3) than the group average (SUS = 70.6), whereas the four postdoc researchers felt that it had low usability (SUS = 47.5). SUS scores of other groups were consistent (within 1σ) of the overall average SUS score.

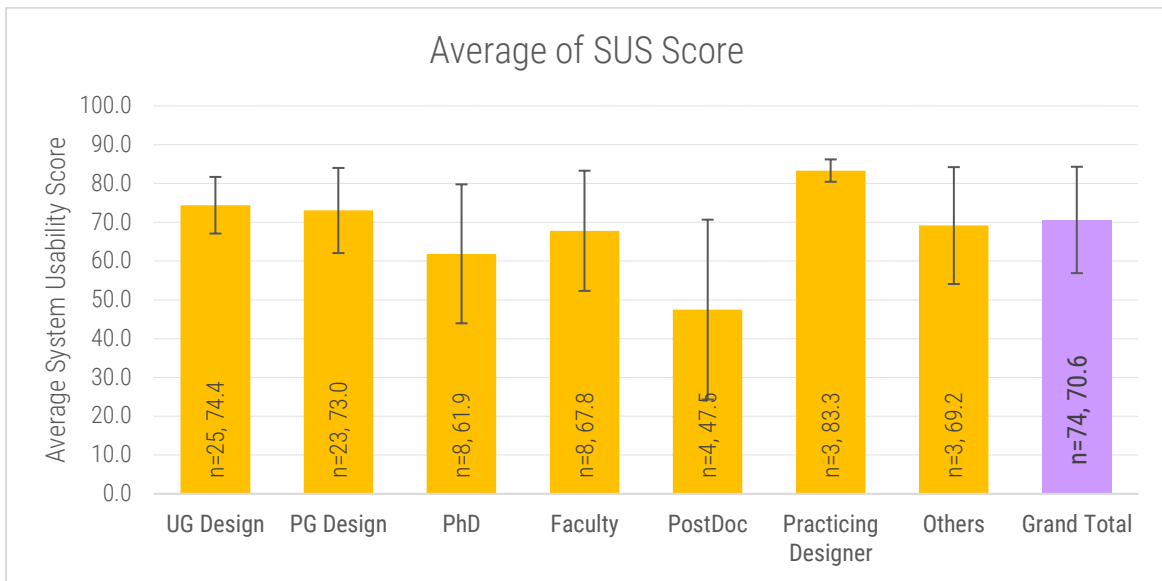


Figure 7.17: Average SUS Score of the FLOW toolkit.

The responses in individual questions of the SUS questionnaire can help understand specific aspects of the toolkit's usability [58]. Figure 7.18 shows the responses to the individual questions of the SUS questionnaire.

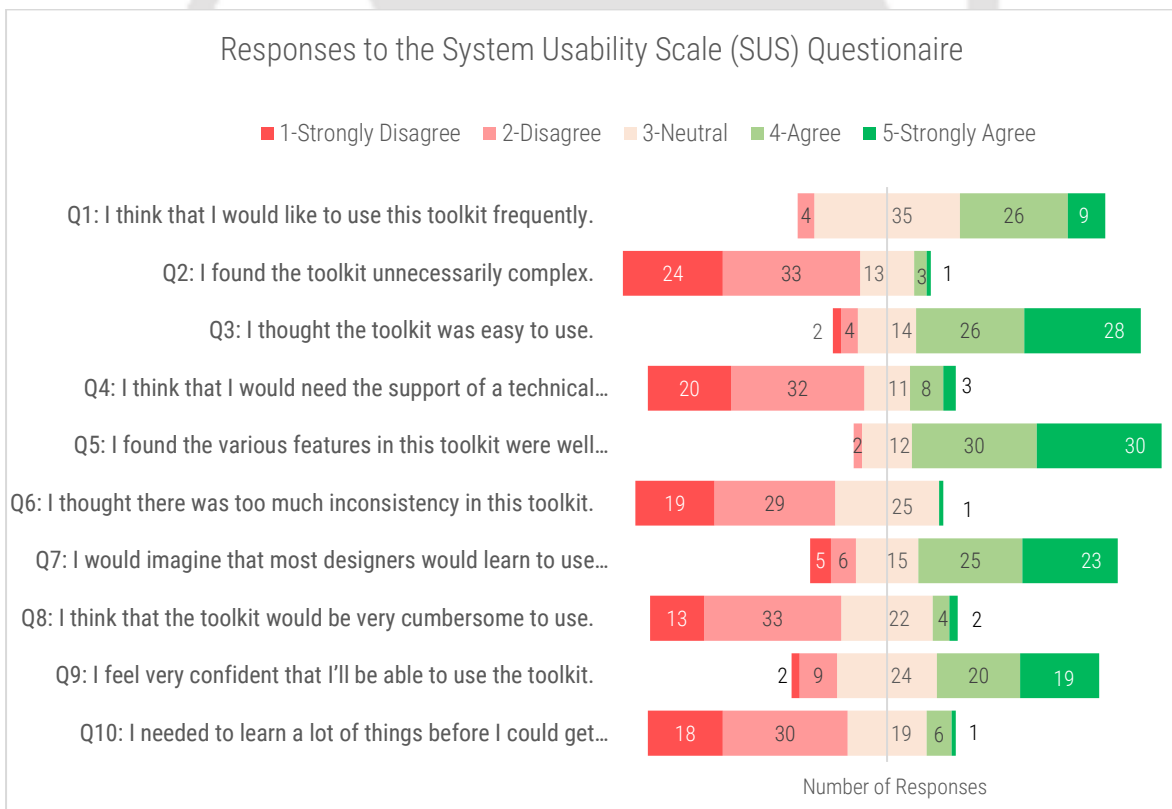


Figure 7.18: Responses to the individual questions in the SUS questionnaire (see Appendix M for questionnaire)

Overall responses to all questions were relatively positive, with most respondents perceiving the toolkit as easy to use (Q3) and not too complex (Q2). Still, some responses show that further explanation and facilitation in implementation might be necessary to improve the toolkit's overall usability (Q4 and Q7). These responses could indicate a higher learning curve for applying the FLOW toolkit in practice. Similarly, Q8, Q9 and Q10 also indicated respondents' perception of a higher learning curve, with many neutral or relatively negative answers.

Regarding the frequency of using the toolkit, respondents were largely neutral (Q1), possibly indicating the niche of the frugal design domain.

Some incongruity in the responses related to the perception of consistency was also noticed. In Q5, most responses were positive, indicating that the toolkit was well integrated, but answers to Q6 show many respondents were neutral considering the inconsistency. These responses indicate that the interconnections and dependencies of various Design Activities were not entirely evident to the respondents when reviewing the toolkit.

Overall, the SUS assessment shows that some improvements are needed to increase the usability of the toolkit. One way to do this could be by reducing the perceived learning curve of the toolkit and making the interconnections between Design Activities clearer. Resources such as explanation videos, example implementations and detailed facilitator guides could be created to improve such aspects. Such resources can be developed by implementing the FLOW toolkit and understanding the usability concerns in participatory workshops.

7.4.2.2 Implementability of the Toolkit

The next analysis step was understanding the toolkit's perceived 'implementability'. Figure 7.19 shows the responses to the questions asked in the survey to understand the overall implementability of the FLOW toolkit. (see **Appendix M**).

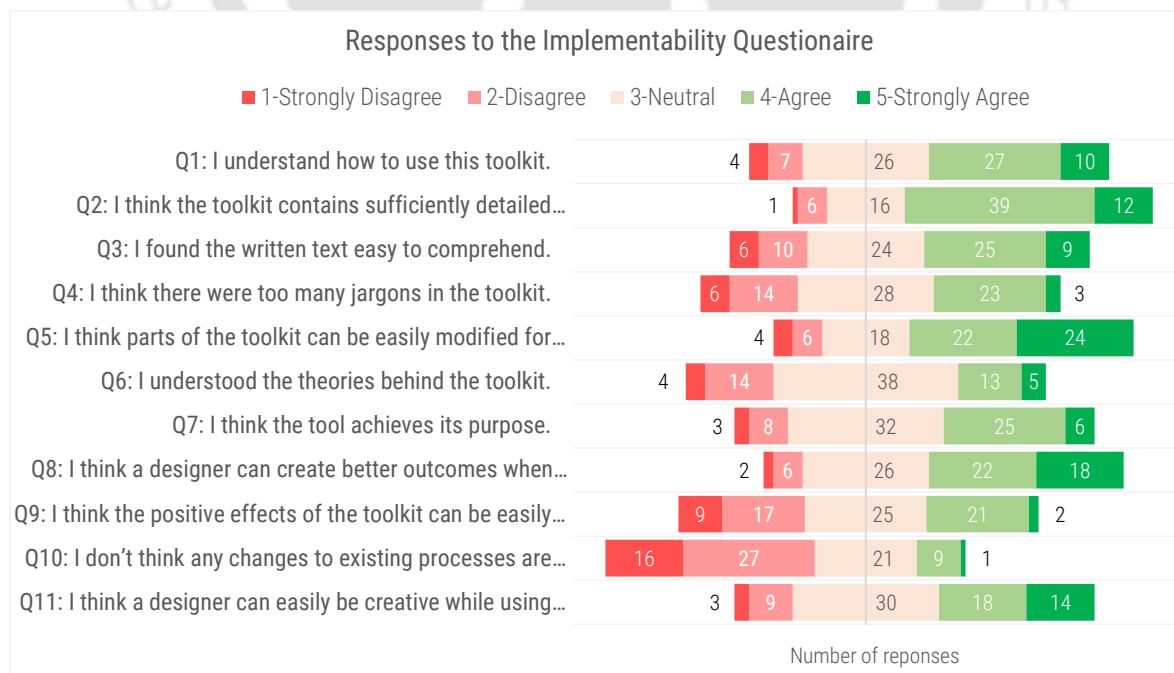


Figure 7.19: Responses to the questions for understanding the FLOW toolkit's 'implementability'.

Overall, respondents agreed that the toolkit could be easily implemented into design practice. Most respondents felt that the toolkit was easy to understand (Q1) and had sufficiently detailed instructions for its use (Q2). Similarly, the toolkit was also perceived as flexible since most respondents agreed to modify it for other purposes (Q5). Most respondents also agreed that the toolkit can result in better outcomes (Q8) and that the novelty of solutions will not be impeded by following the toolkit (Q11).

Still, there are some notable aspects of the toolkit which respondents did not perceive favourably. Although the FLOW toolkit was found to contain sufficient details (Q2), many respondents felt that the text was not easy to comprehend (Q3) and that it contained too much jargon (Q4). Many respondents were also neutral or disagreed regarding the understandability of the foundational theories of the toolkit (Q6). These responses indicate that the text in the toolkit can be improved, focusing on reducing jargon and improving overall readability.

Furthermore, respondents were unclear about the measurability of outcomes. Although most respondents agreed that better outcomes could be achieved using the toolkit (Q8), most were unsure if the positive effects could be easily measured (Q9). These responses indicate that some modifications are necessary to make it easier to measure the quality of outcomes achieved from the toolkit. One way this could be done is by developing specific tools to help measure the outcome quality. Additionally, designers could be provided with resources to show how the toolkit improves overall design outcomes. Such resources and tools can improve a designer's confidence in the toolkit and its implementability.

7.4.2.3 Comparative assessment of the toolkit

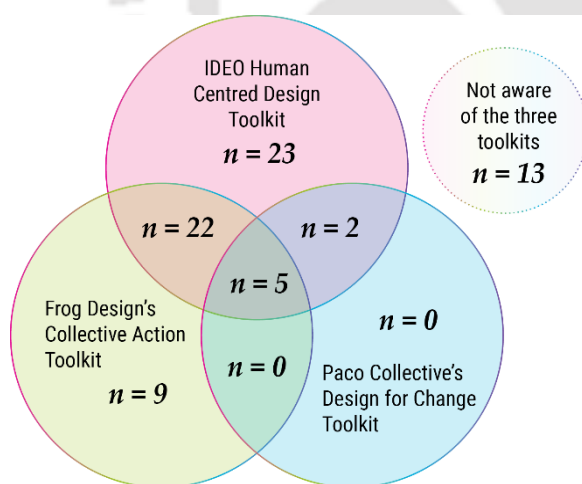


Figure 7.20: Number of respondents who were aware of three existing toolkits related to design for MC.

The survey questionnaire also asked questions for a comparative assessment of the FLOW toolkit (see **Appendix M**). The first question asked if respondents were aware of three existing design toolkits. The options were chosen based on the relative popularity of toolkits³. This question clarified the respondents' awareness of existing supports for design in MC.

Figure 7.20 shows that 70% (n=52) of the respondents knew about the IDEO HCD toolkit [8], 48% (n=36) knew about Frog Design's CAT [11], and only 9% (n=7) knew of Paco collective's "design for change in marginalised communities toolkit" [60]. 14% of the respondents were unaware of any of the three toolkits.

Understanding the awareness of state-of-art provided a grounding to the next two questions. These questions asked respondents to compare the FLOW toolkit with other existing toolkits they

³ Relative popularity of existing toolkits was estimated based on the number of search results in Scopus.com. Total search hits for "human centered design toolkit" was 252, for "collective action toolkit" was 19 and "design for changes in marginalised communities" was none.

knew and the existing design processes they followed on a 5-point verbal scale. Figure 7.21 shows that the responses to these two questions.

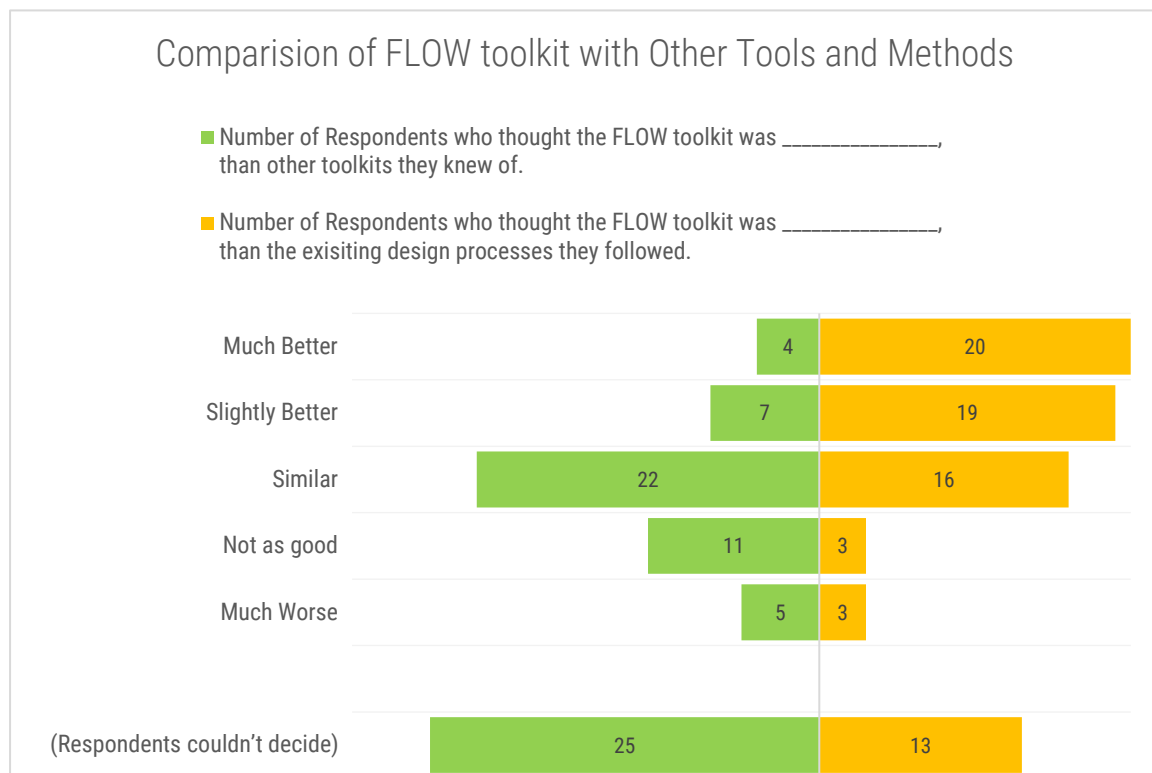


Figure 7.21: Comparison of the FLOW toolkit with existing toolkits and processes.

The figure shows that most respondents perceived the FLOW toolkit as similar to other existing toolkits. Such similarity can potentially reduce the barrier to the adoption of the toolkit. Additionally, most respondents thought the toolkit was better than the existing design processes they followed. This result provides confidence that designers would be interested in using the FLOW toolkit in their practice without much hesitation.

Therefore, combining the insights from the usability, implementability and comparison questions, there is a strong indication that respondents:

- Understood the overall goals of the FLOW toolkit.
- Were clear on how the toolkit could be used.
- Understood how the toolkit could be implemented in a systematic design process.
- Were interested in using the toolkit in design practice.

However, Figure 7.21 also shows that some respondents felt the toolkit was worse than existing toolkits (21%, n=16) and existing processes they followed (8%, n=6). Therefore, there remains some scope for improving the FLOW toolkit in future work.

7.4.3 Discussion on Preliminary Toolkit Evaluation

The analysis provides a basic and preliminary understanding of the applicability of the FLOW toolkit in design practice. The survey found that the toolkit was relatively usable in its current form with an average SUS score of 70.6 ($n=74$, $s=13.7$). The assessment of responses to individual questions from the SUS questionnaire highlighted that there might be a need to reduce the learning curve of the toolkit, showcase the interconnectedness of Design Activities, and improve its readability.

Additional resources such as explanation videos, facilitator guides and tutorial workshops could be conducted to mitigate such concerns and iteratively improve the toolkit's overall usability. Furthermore, participatory workshops are promising for taking the research forward since they can improve the groundedness of the FLOW toolkit and provide better empirical evidence to validate it.

Analysing the responses to implementability questions highlighted that respondents perceived the toolkit was relatively easy to understand, flexible, sufficiently detailed and did not impede creativity. However, concerns similar to those highlighted by the SUS questionnaire were seen. Specifically, respondents could not perceive if the outcomes of the toolkit would be measurably positive. As a remedial measure, design tools to measure the design outcomes and resources to showcase the toolkit's effectiveness in design projects could be developed. Respondents also perceived the FLOW toolkit to be similar to other toolkits, thus providing confidence in its adoption into design practice.

There are some notable limitations to interpreting the results from the survey. In a typical test, the SUS questionnaire is administered after the respondents use the system in question. However, it was not possible in the case of this evaluation. Therefore, the results from the SUS questionnaire can only be considered as perceived usability and must be interpreted with caution. Similarly, the overall validity of the *implementability* questionnaire has not been done since it was adapted from existing frameworks to best suit the task at hand. Therefore, the results can only be interpreted in the context of this study.

Another limitation arises due to the subject selection. The current results are biased towards participants from Asia, most of whom were probably from India due to the process followed. Additionally, since the larger group in the sample were students, the overall results would more closely reflect the perspectives of design students from India. Thus, the outcomes and insights must be interpreted with this fact in mind.

As mentioned before, the ideal way to evaluate and validate the FLOW toolkit would be a mixed-methods approach of participatory workshops, interviews and implementation in design projects. Such a study was out of the scope of this research project due to time and resource limitations and remained future work. Still, the FLOW toolkit can be confidently put to practice with expectations of good results due to empirical evaluations of its theoretical foundations.

Nonetheless, some scope for improving the toolkit were uncovered using this preliminary evaluation. The FLOW toolkit also opens an avenue for further research into frugal design. There is also scope for creating a digital and interactive rendition of the FLOW toolkit. Such a version could accumulate several design tools under a single umbrella and make it easier for designers to navigate and implement the toolkit.

Still, the FLOW toolkit in its current form is a good resource for designers to learn and implement a systematic frugal design process. The toolkit was carefully designed to encourage multiple use cases and designer archetypes to adopt it. However, novice designers could benefit from it the most since it incorporates the extant frugal design guidelines for marginal context into its framework.

Furthermore, the FLOW Canvases can be used as design tools and adapted to support participatory design. Findings from the study on the Frugal mindset have also been incorporated into the toolkit. Based on this, it is argued that the toolkit can also support the development of a frugal mindset. However, this assumption needs to be empirically tested.

The scope of work undertaken in this thesis was completed with the preliminary evaluation of the FLOW toolkit.

7.5 Conclusion

Chapter 7 presented the culmination of research done for this thesis and attempted to answer the second research question by developing a toolkit for supporting systematic frugal design.

The synthesis of the toolkit started with a critical review of analogue design tools and the methodology for their development. This review provided the foundations and a benchmark for designing an analogue toolkit to support a systematic frugal design in marginal contexts.

Comprehensive results and insights from prior research were collected and organised to inform the toolkit's development. These results formed the basis for designing and synthesising **FLOW - the Frugal Design Workflow Toolkit**. The synthesis followed a double diamond approach and extensively employed the FDC and CEH frameworks and the FDC-test workbook from the experimental study. A review of existing toolkits also provided the most suitable modality for operationalising the FDC framework into the FLOW toolkit.

A comprehensive list of Design Activities was developed based on the FDC framework and considering multiple user archetypes and project complexities. This comprehensive list was then refined and iterated, considering the insights from prior research. The final list of Design Activities operationalised into the FLOW toolkit constitute the 'systematic frugal design approach for MC' recommended in this thesis.

The FLOW toolkit was developed by outlining relevant information related to existing design tools, frugal mindset strategies and practically applicable steps for each Design Activity. Such information was directly derived from various studies presented in this thesis.

After synthesising the FLOW toolkit, a preliminary evaluation was conducted to understand its usability and implementability. Overall the toolkit was fairly easy to use and implementable in practice. Still, the evaluation uncovered specific areas for improvement, which is future work for research on this topic.

In conclusion, some considerations for implementing the toolkit and limitations of its evaluation were discussed. One important consideration for the systematic approach prescribed by the FLOW toolkit is that it is limited till the concept development phase. A designer's responsibility in a frugal

design process may include extensive pilot testing and support for development which the toolkit does not currently support. Although the prescribed systematic approach allows for necessary planning of such design phases, the FLOW toolkit may not be adequate in supporting their execution. Still, the FLOW toolkit could be expanded to support such extended stages of the frugal design process in future research.

Finally, this chapter presented the preliminary evaluation of the FLOW toolkit. As discussed, an ideal toolkit evaluation would be using a mixed-method approach. A future research project could focus specifically on iterating the FLOW toolkit through its implementation in live projects or workshops. FLOW toolkit could also lead to developing new tools for collaborative design in MC. Researchers could also consider translating the toolkit into interactive versions and evaluating its effectiveness compared to the physical ones.

This chapter concludes the reporting of various studies and activities conducted for this research project. The next short chapter provides a conclusion to the thesis by outlining the key contributions and insights from the research.

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Chapter 8 Key Contributions and Thesis Conclusion

In this research, we set out to study the topic of '*frugal design for marginal contexts*'. Based on literature review and project experiences, two research questions were selected for examination

- 1 Research Question 1: What will be an effective approach for designing frugal and holistic solutions for marginal context?
- 2 Research Question 2: What will be an appropriate design tool to support a systematic frugal design approach throughout its implementation?

The thesis took a constructivist epistemological stance for answering the research questions due to the research aim and the topic being studied.

The research questions warranted a mixed-method approach where multiple types of studies were conducted to develop a systematic approach, understand its effectiveness and create a design tool. The objectives for fulfilling the research aim were met using extant literature review, case study analysis, action research, experimentation and qualitative studies. In addition, the synthesis of frameworks and the development of toolkits were interpretivist activities.

The thesis presented the **Frugal Design Conceptualisation (FDC) framework** as the prescribed approach for systematically designing holistic and frugal solutions for MC. The approach's effectiveness was experimentally tested by evaluating the framework in a design conceptualisation exercise. These activities, therefore, answered the first research question of the thesis.

The insights from research activities were then operationalised into **FLOW- the Frugal Design Workflow Toolkit**. The toolkit outlined 'Design Activities' developed based on the FDC framework, thus making it suitable for supporting a systematic frugal design approach. Additionally, each Design Activity was structured to provide recommended steps, heuristics, suggestions and tools needed for supporting designers throughout its implementation. The appropriateness of the FLOW toolkit was assessed using a preliminary evaluation of usability and implementability. The results of synthesising and evaluating the FLOW toolkit answered the second research question of the thesis.

This concluding chapter presents the key insights and outcomes presented in this thesis.

Section 8.1 below discusses the critical insights and outcomes from each thesis chapter. The insights relevant for developing the systematic approach for frugal design in MC are highlighted. The section discusses the implication of the outcomes for design in MC and design practice in general.

Section 8.2 and 8.3 discuss the research's overall limitations and the directions for future research needed to enrich our understanding of a systematic 'frugal design' process.

8.1 Key Outcomes and Insights

Donning a researcher's hat brought forth many unanticipated challenges and lacunae related to frugal design for MC.

In the extant literature, it was found that several foundational aspects, including defining 'frugal design' and the design process for MC, were not adequately addressed. Similarly, literature was divided on what was considered a 'Marginal Context'. These were first addressed in chapter 1 by undertaking a comprehensive literature review of relevant domains related to frugal design and MC. Based on this extant literature review, 'Frugal Design' can be defined as follows:

'Frugal design' or 'a frugal design process' is a low-resource consuming design process for developing sustainable and holistic solutions available to users at significantly low costs and perform optimally to adequately meet the needs of stakeholders in a design context. Outcomes of such a process can be called frugal design solutions or frugal designs.

Similarly, the literature related to poverty and its environment were scrutinised from the perspectives of sociology, economics, marketing and innovation to define the construct of 'Marginal contexts' for this thesis as follows:

Marginal Contexts (MC) are social scenarios within a specific geographical boundary where the people have low income, low capabilities, low freedom and lack access to infrastructure and institutional support.

The next step in the extant literature review was to understand frugal design from the perspective of design-related literature to define the scope of a 'systematic' frugal design process. This exercise helped outline an insightful list of design guidelines and recommendations for product design, strategic design and dissemination of frugal design solutions. Additionally, several proposed frameworks for the systematic design of solutions for MC were also uncovered.

However, the outcomes highlighted a lack of systematic and empirically validated design frameworks, processes, methods and tools to support frugal design in MC. This review also uncovered the phenomenon of a 'frugal mindset' that was essential to the process but was not adequately explored.

The chapter laid out the research plan, aims and objectives. These included:

- Objective 1: To identify the recommendations for frugal design in MC.
- Objective 2: To identify the important strategies related to frugal design.
- Objective 3: To understand the challenges and constraints in frugal design.
- Objective 4: To develop frameworks for systematically conceptualising and evaluating frugal design solutions.
- Objective 5: To empirically verify the effectiveness of such frameworks.
- Objective 6: To understand the phenomenon of 'Frugal Mindset.'
- Objective 7: To develop a design tool to support frugal design in MC.

Each of the studies and research activities reported in this thesis was devised to effectively meet these seven objectives and were sequentially presented through Chapters 1 to 7. The contributions

of each chapter progressively addressed the research questions and contributed to validating the different insights and outcomes described below.

Chapter 1 discussed the various **frugal design guidelines and insights**, whereas Chapter 2 **provided grounded evidence** to support them by analysing existing case examples. Chapter 2 analysed a sample of successful and failed solutions in two related exercises. Analysing successful solutions resulted in understanding **critical focus areas** when designing products of certain types. On the other hand, analysing the failed solutions for MC led to the **synthesis of specific strategies for implementing design guidelines in practice**. These focus areas and strategies formed the basic building blocks for developing a systematic approach for frugal design in the later Chapters. In addition, the chapter provided some **insights on how solutions fail in MC** and **ways to assess solution complexity** in frugal design projects.

The second study, presented in Chapter 3, undertook a **retrospective analysis of four product design projects done for MC**. This analysis aimed to gain the deepest possible understanding of frugal design and fully appreciate the challenges and constraints of developing products for MC. The study resulted in a **list of constraints that affect the design process** and **critical requirements for a systematic approach** to frugal design.

Chapter 4 presented an exercise where insights derived from the literature review, analysis of case examples and the retrospective analysis were utilised to synthesise **two novel frameworks** for a systematic frugal design approach in MC. The chapter also presented a **critical review of existing approaches** and methodologies prescribed for designing in MC. Findings from the review and prior research led to the synthesis of **the Frugal Design Conceptualisation (FDC) framework**, a systematic approach for designing holistic and frugal solutions for MC. In addition, a novel framework called **Contextual Evaluation Hierarchy (CEH)** was proposed for understanding the constraints in an MC and evaluating frugal solutions at early design phases. Ways of **practically implementing the FDC and CEH frameworks** in design projects were also discussed in the chapter. With this, the first research question in the thesis was partially answered.

However, to fully answer the first research question, it was essential to understand the effectiveness of the proposed design approach. Chapter 5, therefore, presented the third study of the thesis, where the **effectiveness of the FDC framework was empirically tested** using a design conceptualisation exercise. In a **repeated-measures study design**, concepts generated using the frameworks were compared with those generated without them. The study provided satisfactory evidence that **the FDC framework enabled better systematic conceptualisation of frugal design solutions for MC**.

Additionally, the experiment also helped understand the effectiveness of the CEH framework in the subjective evaluation of design concepts. It was found that **the CEH framework could effectively direct a frugal design process and help in evaluating solutions at early design phases**. The FDC and CEH frameworks formed the basis for a **comprehensive and systematic approach to conceptualise holistic and frugal solutions for MC**, which could be translated into appropriate design tools.

The extant literature review emphasised the importance of a little known and unique phenomenon when designing for MC called the 'frugal mindset'. **Implementing a frugal design approach depended on a unique 'mindset'** that went beyond the typical designer skillsets. Therefore, a study in the thesis was dedicated to understanding the frugal mindset phenomenon and

identifying strategies to imbibe it. The aim was to learn about it enough to meaningfully append the design of a tool following the systematic approach prescribed in the FDC framework.

Chapter 6 presented a qualitative study where **12 experts were interviewed** to identify unique strategies for implementing a frugal mindset in a design process. Existing cognitive psychology theories were used to develop a **framework for understanding frugal mindsets** and a questionnaire for semi-structured interviews. Analysis of the interviews resulted in a **set of unique strategies designers use for imbibing a frugal mindset** when executing design projects for MC. **'Frugal mindset' was described** as follows in the context of this research:

A 'frugal mindset' is an overall mindset that emerges in a designer who employs the unique strategies identified when designing appropriate solutions for marginal contexts to satisfactorily meet users' needs.

Other significant outcomes of the study presented in Chapter 6 were identifying strategies used by designers to **find new design opportunities and their motivations** when developing solutions for MC, thus providing a comprehensive understanding of the little-understood phenomenon of frugal mindset.

Finally, Chapter 7 presented the culmination of the thesis work and attempted to answer the second research question by developing a toolkit for supporting systematic frugal design. The overall insights from prior research formed the basis for designing and synthesising **FLOW - the Frugal Design Workflow Toolkit**. The synthesis followed a double diamond approach and extensively employed the FDC and CEH frameworks and the FDC-test workbook from the experimental study. The **Design Activities operationalised into the FLOW toolkit constitute the 'systematic frugal design approach for MC'** recommended in this thesis.

The chapter also reported a preliminary evaluation of the FLOW toolkit to understand its usability and implementability. Overall the **toolkit was reasonably easy to use and implementable in practice**. Still, the evaluation uncovered specific areas for improving the toolkit, which was an avenue for future researchers to take the research forward.

In summary, the key insights, findings and outcomes of the thesis were as follows:

- An extant literature review uncovered a comprehensive list of frugal design guidelines and recommendations and resulted in defining relevant terminologies for frugal design in MC.
- It was understood that a Frugal design process needs to integrate deep user and context understanding, Product design methodologies, Novel strategies for service and business, and methods for effective dissemination of solutions in the MC.
- Designing different types of solutions for MC may need a different focus during the development process. The research uncovered several 'focus areas' for developing different solution types during a frugal design process.
- Analysis of case examples indicated that not all frugal design guidelines are equally applicable for all solution types. A list of essential design guidelines that must be implemented in a frugal design process and accompanying strategies for their practical implementation was developed.
- Research uncovered the modalities of how solutions fail in MC, which led to an understanding of characteristics of project complexity in a frugal design process.

- Two novel frameworks for supporting the frugal design process were synthesised – the FDC framework and the Context Evaluation Hierarchy. Methods for practically implementing the frameworks in a design process were outlined.
- An empirical evaluation of the FDC framework clarified that the framework effectively enabled designing better holistic and frugal solutions than a typical design process. Additionally, the CEH framework was revealed as an adequate ‘support’ for the subjective evaluation of frugal design solutions in the early design stages.
- The phenomenon of frugal mindset was understood, and specific strategies for imbibing it were discovered. In addition, the motivations of designers with a frugal mindset were found.
- Unique strategies employed by designers in finding novel opportunities for developing holistic solutions in MC were identified.
- Novel design support called the FLOW Toolkit was developed, which operationalised a systematic frugal design process based on the FDC framework and incorporated the insights from the overall research.
- A preliminary evaluation of the FLOW toolkit found that it was perceived to be reasonably usable and implementable with some scope for improvement.

The outcomes and insights indicated that the research adequately answered the two research questions and met the thesis aim and objectives.

8.1.1 Implications of Outcomes

The outcomes of this research provide significant clarity on how designers must approach the development of holistic solutions for MC. Although many design guidelines can be found in literature, their practical implementation was limited due to a lack of tools and supports that considered the constraints designers faced in MC. The FLOW toolkit provides designers with a way to ensure many such guidelines, if not all, are met when executing a systematic frugal design process.

The work presented in chapter 2 also provided some qualitative validation to the various guidelines associated with designing for MC. Additionally, the work highlighted some critical guidelines essential for practical implementation in a design process for MC.

Incorporating the critical design guidelines into the FLOW toolkit promises that the problem of ‘rebound effect’ associated with frugal innovations is somewhat mitigated. Designers employing the FDC framework and the FLOW toolkit are prompted to consider the product lifecycle, consumption, and sustainability aspects of a design solution throughout the process. The toolkit also prompts designers to measure a solution’s success using wellbeing and capability improvements rather than purely performance metrics. Designers are directed towards tools to assess and implement sustainable design and ‘capability approach’ at early design phases. Therefore, there is arguably a reduced chance of challenges arising from a ‘rebound effect’ due to such considerations.

Most crucially, the FDC framework outlined the critical ways in which the frugal design is different from a typical design process. A frugal design process involves designing a holistic solution and deeply understanding its impact on the context early in a design cycle. The process is

equally focused on detailing product embodiments and holistic aspects of a solution for its effective implementation in MC. The process incorporates unique two-phased design research for gaining a complete understanding of the MC and the stakeholders of the solution. Finally, an effective frugal design process incorporates three types of co-design activities for understanding, ideation and evaluation of the solution. Such characteristics make frugal design significantly different from a typical product design process.

The frugal design approach presented in the FDC framework and FLOW toolkit is arguably more effective than several existing 'design for MC' approaches and toolkits. The prescribed approach considers product and solution proposal design in more depth. Similarly, it meets the shortcomings of the existing product-service system and appropriate technology approaches discussed in Chapter 1 since it considers the embodiment and holistic aspects in equal detail. The FLOW toolkit also mitigates the shortcoming of some existing toolkits that ignore the effect of multiple stakeholders on the solution by keeping the design only user-centred. Since a frugal design approach embraces the social ambiguities of design in the MC and considers the solution's effect on the entire populace in the context, Frugal design can be understood as a **social-centred design approach** rather than purely a user-centred approach.

8.2 Limitations and Scope for Future Research

There are some overall limitations to this research that must be noted. These limitations provide vital directions for future researchers who wish to research this domain in the future

The literature review majorly considered the publications until late 2020, and new research published afterwards was not considered. Similarly, the review may have overlooked some essential insights not related to the selected search domains. There is scope for an updated systematic literature review on 'frugal design' where such lacunae can be adequately addressed.

The case study analysis focused on qualitative depth and was undertaken with relatively small sample sizes. However, the study could be viewed as a stepping stone in formulating and developing a structured approach to frugal design. The proposed frameworks must therefore be interpreted within the context of this research. Similarly, the retrospective analysis of projects was qualitative and dependent on the researcher's immersive and experiential worldview. Although the results provided significant insights to inform design practice, it will be interesting to revisit its interpretation in future research where a large sample of design solutions and projects are analysed.

The synthesis methodology followed for developing the FDC and CEH frameworks presented in Chapter 4 were qualitative, inductive and dependent on the researcher's worldview. The work was justified considering an interpretivist epistemological stance in the context of this thesis. Thus, even if a systematic and rigorous process was followed in developing the frameworks, it must be considered one of the possible ways to synthesise the insights from prior studies. Other attempts at developing such a framework may result in some variation, but it may help to further enrich the research processes.

Similar cautions in interpreting the insights must be kept when implementing the FDC and CEH frameworks. The practical implementation of the framework depends on developing appropriate

Design Activities that meet the objectives of the FDC framework. Although this provides flexibility to the designer, it also imparts a layer of subjectivity. Developing the Design Activities for the FLOW toolkit resulted from such a subjective and interpretative exercise, and some variation can be expected if it is replicated.

An interesting future study could consider contrasting the outcomes from two such varied implementations of the FDC framework. Such a study could help validate the overall effectiveness of the frameworks further and provide novel insights into a systematic frugal design process.

Another important note is that the scope of the systematic approach, prescribed by the FLOW toolkit and FDC framework, is limited till the concept development phase. A designer's responsibility in a project may include extensive pilot testing and support for development. The frugal design approach prescribed by the FDC framework and FLOW toolkit only allows for planning such design phases and may not support their execution. Still, future researchers can expand the FLOW toolkit to accommodate the execution of such trailing phases and present a more elaborate version of the toolkit.

The results of the experimental evaluation of the FDC framework must be interpreted with some limitations. Although some evidence was uncovered to support the effectiveness of the FDC framework with participatory approaches, it was not thoroughly tested. Such testing requires more rigorous and focused studies in future research. Similarly, the effectiveness of the CEH framework was also tested in similar controlled conditions. Therefore, design concepts evaluated using CEH can be evaluated in future studies to verify if they result in marketable solutions.

The study on the frugal mindset reported in Chapter 6 followed a rigorous analysis of interviews to understand the phenomenon. Due to the limited sample selected and the chosen methodology, the outcomes do not represent a general theory to explain the frugal mindset. Although a novel attempt was made to provide a framework for its understanding, the results must be understood as preliminary pointers that require further research in the future. Furthermore, the overall analysis may not have reached saturation due to the limited sample size. Therefore, there is some scope for future research projects to focus specifically on 'frugal mindset' and create a more generalised theory leading to appropriate design supports.

Finally, Chapter 7 presented the FLOW toolkit and its preliminary evaluation. An ideal evaluation of the toolkit would have been using a mixed-method approach. This work was not considered within the research scope due to resource limitations and some challenges presented by the Covid-19 pandemic. A future research project directly based on this thesis could work specifically on such an iterative refinement of the FLOW toolkit. Researchers could evaluate the toolkit's effectiveness in live design projects and through workshops. Future research could also consider translating the FLOW toolkit into interactive versions and evaluating its effectiveness compared to physical ones.

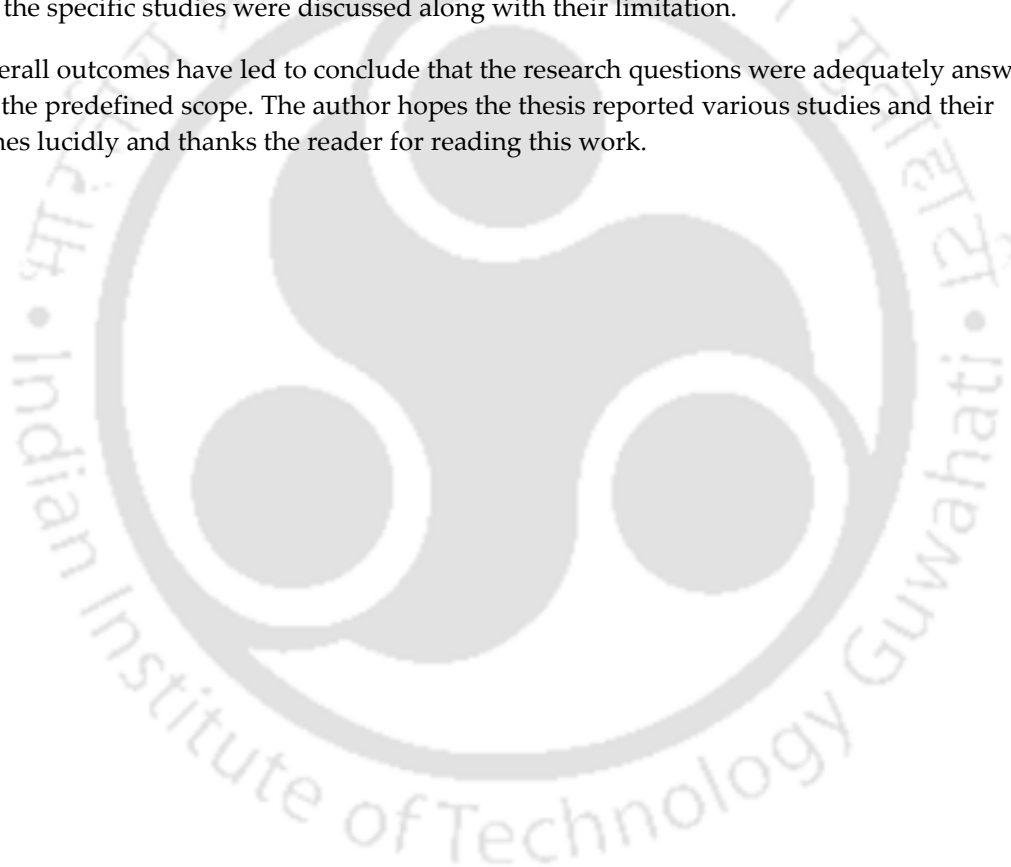
8.3 Closing note

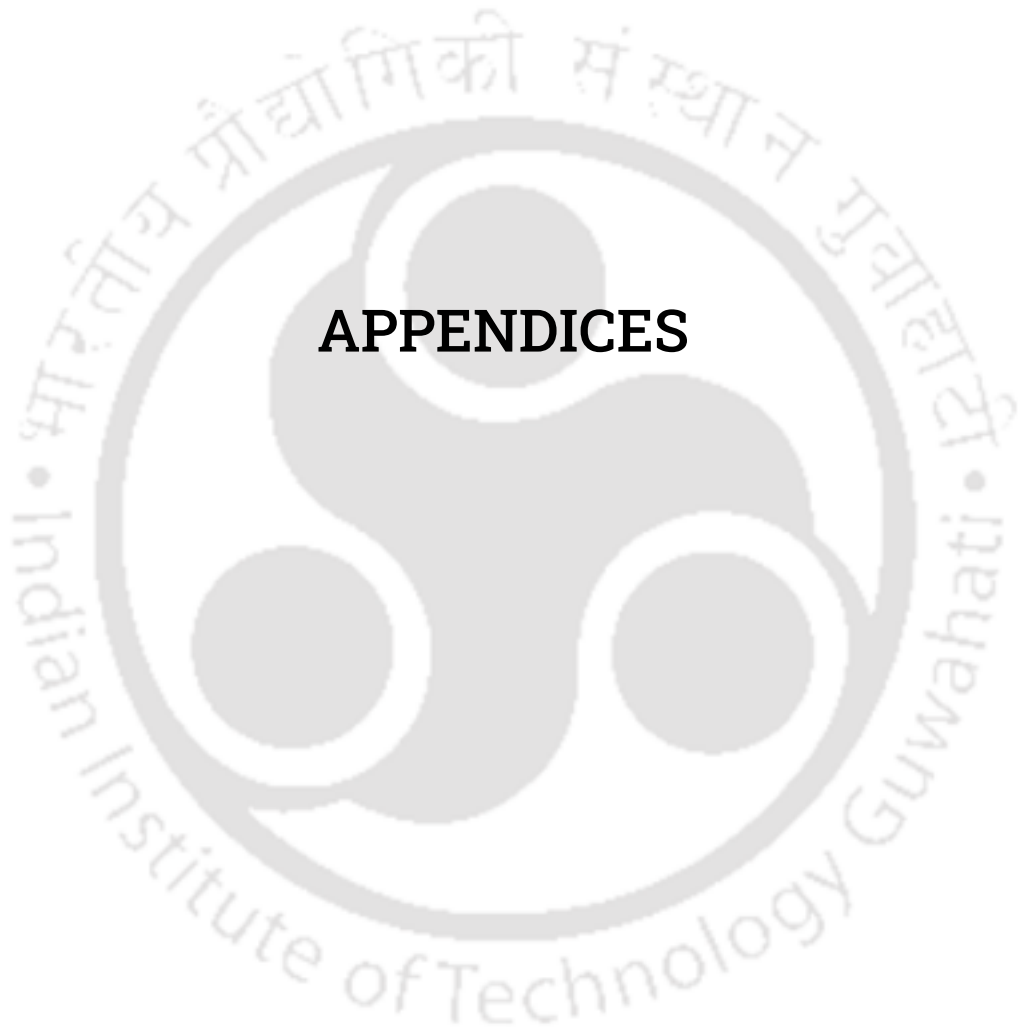
The central thesis of this research is the presentation and evaluation of frameworks for systematically designing holistic and frugal solutions for MC and a toolkit for their practical implementation.

In this concluding chapter, the significant outcomes and insights from various studies in the thesis were recapitulated. The chapter also discussed the implications of these outcomes and insights on the topic of frugal design, presenting arguments for its effectiveness.

Some general limitations of the research studies and the considerations for interpreting their outcomes were also discussed. These limitations highlighted some crucial directions for future researchers to expand the work presented in this thesis. Additionally, future research that could extend the specific studies were discussed along with their limitation.

The overall outcomes have led to conclude that the research questions were adequately answered within the predefined scope. The author hopes the thesis reported various studies and their outcomes lucidly and thanks the reader for reading this work.





APPENDICES

Appendix A – Frugal Design Guidelines

The following tables present a detailed list of design guidelines and recommendations derived from an extant literature review (see Chapter 1). The guidelines have been divided into three sections: Design Process, Business models and Strategies, and Execution and Dissemination. The first column of each table lists the lifecycle stages to which the design recommendations are related. References are listed after the tables.

Table A.1: Guidelines and Recommendations related to Design Process.

Product Lifecycle Stage	Recommendations and Guidelines related to Design Process
Product Design	<ul style="list-style-type: none"> • Increase the design project’s scope to ‘meeting’ of intrinsically valued needs rather than the design of a product. Design a holistic solution (or a set of solutions) that goes beyond just a tangible artefact. Aim to meet such needs through any possible means in the context. [1], [2] • Develop a deep understanding of the user’s way of life and the ‘intrinsically valued wishes’ that the user wants to meet by using the product. Understand the basic and important needs that have not been satisfactorily met. Aim to meet such needs through a holistic solution [1], [2]. • Design the product to be ‘de-skilled’ such that it does not require any prerequisite knowledge or education to operate as far as possible. Use instructions, interactions and mental models that can be easily understood by low-literate users and users of all socio-cultural backgrounds [3]. • Design affordable products by: <ul style="list-style-type: none"> ○ Focusing on achieving one core functionality only [4], [5], OR ○ Adding more value by designing multi-functional products and keeping price low [6], OR ○ Changing the product architecture to achieve the same functionality given by non-affordable products [7], [8], OR ○ Reconfiguring of existing components to reduce the overall cost. [9] • Design products that have a large life span are durable and robust to use. [2] • Consider lack of knowledge and skill in the user when using the product. Design products that accept intended or unintended errors in usage. [10], [11]
Product Manufacturing	<ul style="list-style-type: none"> • Use methods for task design to develop products that reduce cognitive complexity, physical complexity and effort in assembly and manufacturing. Task design methods include QFD, design of Jigs, Fixtures, DFMA and Visual control [12]. • Design solutions that can be manufactured with low level and frugal infrastructure [3]. • Use Loose and inaccurate tolerances in designs. Use standard parts wherever possible [13]. • Design products that work reliably across their lifetime, even in extreme environmental conditions and unreliable maintenance. Examine and imagine unanticipated usage scenarios for new technologies using tools such as Failure Modes and Effects Analysis [6], [13], [14].

Product Distribution /Purchase	<ul style="list-style-type: none"> • Design products that are scalable, easily transportable, easily deployable and in large numbers. The product should be robust to the variations and difficulties in transportation [3], [13]. • For communication design aspects of the product, consider using non-traditional means of advertisement, branding, packaging and product promotions. For example, consider using: low-cost theatre presentations, vehicle-mounted advertisements, collaboration with known and respected local personalities and endorsements from local technically knowledgeable persons. [2]. • Communication design should be to reduce the inherent mistrust in the BoP community [15].
Product Use	<ul style="list-style-type: none"> • Design the products to be robust, dependable, and work under unreliable environments, energy, and raw material supply [16], [17].
Product Servicing	<ul style="list-style-type: none"> • Design the associated services to require the user very little effort and time to avail the service. The services associated with the product design should be usable and informative to a person of the lowest literacy [2], [18], [19]. • The product should be designed such that they are modular and can be easily upgraded, modified and updated to offer a newer and better functionality [14], [20]–[23].
Product Recovery /Disposal	<ul style="list-style-type: none"> • Design products where biological and technical nutrients can be recovered easily and with accessible infrastructure within the proximity of the local context. [3], [18], [21].

Table A.2: Recommendations and Guidelines related to designing Business Models and Strategies.

Product Lifecycle Stage	Recommendations and Guidelines related to designing Business Models and Strategies
Product Design	<ul style="list-style-type: none"> • Plan the product and business models to meet the affordability of the customers using a combination of the following: <ul style="list-style-type: none"> ○ Reducing the total Lifecycle costs of the product [2]. ○ Incorporating provisions for deferred payments, microfinance, cashless transactions, mobile payments or Pay-per-use models [2], [18], [20]. ○ Consider a PSS based approach for business model design [2], [3], [18]. ○ Packaging in smaller sizes (after due considerations of sustainability aspects) [2], [24]. • Design an 'inclusive' business model which incorporates the local stakeholders into the value chain as much as possible. The BOP population should be able to transform themselves into producers and entrepreneurs by being part of the value chain [24]. • Design a strategy for scaling up the designs at the early stages of the process and develop a long term sustainability plan for the business. Consider the long term consumption practices of the products and services [9], [25].

Product Manufacturing	<ul style="list-style-type: none"> • Develop and incorporate processes that can scale up to meet a bigger demand with good quality [25]. • Partner with local entities and organisations to develop the support infrastructure required for product development at the early design stages. Plan design and development activities close to the design context. Consider decentralising the manufacturing facilities and develop a distributed model for manufacturing and service [25]–[27]. • Pursue solutions that are sustainable across its lifecycle and motivate sustainable use of resources [28], [29].
Product Distribution /Purchase	<ul style="list-style-type: none"> • Develop partnerships with local non-traditional partners for developing the capacity. Non-traditional partners are NGO's, government bodies, individual grassroots innovators [30]–[32]. • Design innovative and adaptive methods for product distribution for locations that are difficult to reach or those that lack infrastructure. Solutions that can be considered include mobile outlets, Agent-based distribution, community-based distribution, a local entrepreneur based distribution etc. [9].
Product Use	<ul style="list-style-type: none"> • Provide financial support and microfinance for product ownership and maintenance by collaborating with local financing organisations [2]
Product Servicing	<ul style="list-style-type: none"> • It is important to understand the proximities and the relation between proximities to understand and make decisions for the BoP Businesses [25]. • Consider a pay per use or 'servitized' model for delivering the product to the customers[2], [18], [33].
Product Recovery /Disposal	<ul style="list-style-type: none"> • Consider providing services for product update, modification, repair, and take back [2], [34], [35].

Table A.3: Recommendations and Guidelines related to Execution and Dissemination of the solution

Product Lifecycle Stage	Recommendations and Guidelines related to Execution and Dissemination of the solution
Product Design	<ul style="list-style-type: none"> • The designer's engagement with the product should continue until a stable situation of product use is achieved and the product can provide the 'desired ends'. The designer should iterate on the product till the 'desired end' is met [1]. • The execution of the design project should be considering the broader goals relating to technology, socio-ethical considerations, environmental and business considerations. The designer should immerse herself into the local culture to understand the socio-ethical and cultural aspects of the solutions. She should Develop a deep understanding of the culture of the context and integrate its aspects into the product or service [3], [13], [36], [37]. • Incorporate local stakeholders into the design process to make up for the deficiency of understanding the local context. Locally placed organisations, such as NGOs, can be considered partners in all stages of the design process. Designers should play the role of facilitators for the co-creation of solutions. The co-creation of solutions should be done with all stakeholders and users of the intended solution [1]–[3], [21], [33]. • Business should be done with goodwill and considerations to the local communities, cultural and social practices [34], [38]

	<ul style="list-style-type: none"> • Provide income generation opportunities to local entrepreneurs and stakeholders by being part of the value chain. Consider incorporating a larger percentage of women in the value chain as partners [21], [26], [39], [40].
Product Manufacturing	<ul style="list-style-type: none"> • Consider incorporating larger labour and human resources in manufacturing. This can be done more in low labour cost areas [2]. • Leverage local infrastructure, materials, resources and workforce for manufacturing, production and development costs. Consider allying with local inventors and innovators for the R&D of the product. Device method for manual rather than automated processing [9], [33], [41], [42]. • Consider lack of knowledge and skill of the manufacturing labour and design for minimum errors during manufacturing and assembly [43].
Product Distribution /Purchase	<ul style="list-style-type: none"> • Plan the distribution considering the long-term consumption practices. Consider incorporating local bodies, government agencies and other local social networks to support the supply network for the product [25]. • To mitigate the problems with delivery to remote locations, the difficulty of rural outreaches for physical delivery of the products. Local organisations are useful in obtaining market intelligence [9], [33], [41]. • Target to bring the cost down to the level of the current substitutes used by the user for meeting the same needs or below. Benchmark the product pricing with the existing substitute that the people use for fulfilling their needs and not another product [8]. • Develop a strong brand for the product or service which is rooted in the local culture or is supported by existing trusted entities already functioning in the context [6], [10]
Product Use	<ul style="list-style-type: none"> • Provide training and education for the effective use of products and services. Provide entrepreneurial training to stakeholders who are part of the value chain. [2], [9], [31] • Use local stakeholders and local bodies to build confidence and trust in the brand and services being provided. Use locally influential personalities to deliver the product and service know-how [2], [33], [44]. • Provide Technical support and infrastructure to support entrepreneurs for setting up ventures to support the product network [31]. • Develop local stakeholder and social networks to ensure sustained engagements with the business [44].
Product Servicing	<ul style="list-style-type: none"> • Reduce the perceived time and effort that the customers need to buy or use a service. Use Jargon-free terms when offering service. Make the user feel inclusive unembarrassed, and clear despite the knowledge that he is illiterate [40]. • Consider a word-of-mouth-based reference system for implementing financial transactions [40].
Product Recovery /Disposal	<ul style="list-style-type: none"> • Design product that when used in mass-scale does not translate into bad resource consumption habits. Eliminate, or minimise parts that may end up in landfills or water bodies. [7], [45] • Device mechanisms to proactively scout for obsolete, broken and unused products and set up a system for local repair [14].

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Appendix B – Implementation of CEH framework

Table B.1 shows a proposed way for implementing the Context Evaluation Hierarchy (CEH) framework for directing research activities in frugal design projects in MC. (See Section 4.3 for details. Table 4.8 presents a part of the table below.) For each parameter in CEH, a possible design research question and activity needed to answer the questions is presented. Designers can also identify other research questions based on the description and keywords for each parameter.

Table B.1: A proposed way for implementing the CEH framework for directing research activities.

CEH Parameters	Design Research Questions to answer	Design Research Activities to conduct
Environmental and Geographical Conditions	How will terrain, climate and environment affect the possible solution? Will the context's location affect the deployment of design solutions?	Field visits to prominent locations in the context. Analysis of transportation of goods in the context. Interviews with stakeholders
Organisation of Social Networks	Which prominent social group can the solution providers collaborate with? Will the solution affect the social dynamics in the context? Will it be a positive or negative impact?	Interview with visionaries and agencies in the context. Focus group interviews with prominent people in the context.
Religious and Cultural Beliefs	Will the cultural and religious practices be compatible with the envisioned solution? Which social practices are hard to change? How does the envisioned solution affect these? Are there any cultural and social segregations that may affect the implementation?	Demographic information. Observational Studies of existing cultural, religious practices and rituals. Observational Studies of users. Interviews and Focus groups to understand cultural practices.
Financial Security of the People	What financial support do people currently have? What are the issues faced by institutions in providing financial support to the people in the context?	Survey of supporting institutions and social programs. Interviews with various supporting agencies and institutions.
State of Legal Enforcement	What are the capabilities that people lack? Can a solution help in improving these? What are the legal challenges in implementing a solution in the context? What is the scope of intellectual property safeguard in the context?	Observational studies and analysis of user's daily lives. Interviews with government agencies, NGOs and supporting agencies. Collaboration with legal and law enforcement agencies.

Political Practices	<p>How can prevailing political practices and ideologies affect the implementation of a solution?</p> <p>Who are the community leaders in the context?</p>	<p>Interviews and collaboration with community, social and political leaders.</p> <p>Focus group interviews with stakeholders and visionaries.</p>
Access to Production Processes	<p>What are the easily accessible methods of production in the context?</p> <p>Which vendors can be partnered with?</p>	<p>Field visits and observational studies</p> <p>Collaboration with production partners</p>
Access to Infrastructure	<p>What is the state of electricity, roadways and other such infrastructural facilities?</p> <p>What are the challenges in accessing existing infrastructure in the context?</p>	<p>Observational Studies and Interviews with stakeholders</p> <p>Survey and observational studies of necessary infrastructure facilities.</p>
Access to Raw Material	<p>What are the commonly used and abundantly available raw materials in the context?</p> <p>Which are some culturally meaningful materials?</p>	<p>Observational Studies of users households</p> <p>Field Visits to prominent cultural locations in context</p> <p>Interviews with users</p>
Access to Skilled Manpower	<p>What are some of the educational and vocational institutions in the vicinity?</p> <p>How can unemployed youth in the context who can be included in the value chain?</p> <p>What are some of the skill-driven crafts practised by locals? How can these be leveraged?</p>	<p>Demographic Analysis</p> <p>Survey of educational and vocational training centres</p> <p>Survey of craft, handloom and other skilled practices in the context.</p> <p>Interview and Focus groups with visionaries.</p>
Access to Markets	<p>How are the supply chains of existing solutions structured?</p> <p>What are some of the established supply chains in the context, and how can they be leveraged?</p> <p>What are the retail, wholesale and distribution practices?</p>	<p>Survey of markets and existing solution providers</p> <p>Benchmark product analysis</p> <p>Interviews with market players</p>
Purchasing Capability	<p>What are the common professions of the people?</p> <p>How much do people earn, and what are their spending habits?</p> <p>What are the common items in possession?</p>	<p>Observational Study and Shadowing of users.</p> <p>Survey of household income and spending habits</p> <p>Interviews with users</p>
Health and wellbeing of the people	<p>What are the wellbeing risks that people face in the context?</p> <p>How do health and wellbeing affect the solution?</p> <p>What are the common diseases and health hazards in the context?</p>	<p>Field visits and observational studies of the context</p> <p>Interview with healthcare professionals and social workers</p> <p>Interview with users</p>

<p>Literacy of the People</p>	<p>What is the level of educational qualification of users?</p> <p>What is the access to training, education and vocation users have?</p> <p>Can the solution be used by people who cannot proficiently read or write?</p>	<p>Interview with stakeholders.</p> <p>Survey of educational and vocational training centres.</p> <p>User testing of prototypes.</p>
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Appendix C – Design Workbooks

The design conceptualisation exercises (DCE) reported in Chapter 5 uses two workbooks. The first workbook is the NPD-test workbook which helped subjects systematically execute the NPD approach for concept generation. The second workbook is the FDC-workbook that helped subjects implement the Frugal Design Conceptualisation (FDC) framework. Contents of the **workbooks** are shown below.

C.1 NPD-test workbook

Concept Generation Exercise

In this exercise, you will need to design a product concept based on a given brief related to the base of the pyramid context washermen community in Guwahati. The exercise will last for a maximum of 3 hours.

Your goal for this concept generation exercise will be to:

- Design as many ideas as possible for the given design brief.
- Choose a set of ideas and create a single detailed concept for the given design brief.

Your concepts will be evaluated by experts based on:

- Quality of the final design concept presented.
- The clarity in communicating.

Follow the steps below sequentially for designing the concept

Step 1: Refine and Reformulate the Design Brief

Redefine and write a new design brief based on your assessment of the context and the information provided during the lecture session. The brief can be redefined to reflect your understanding of the best possible way of solving the problem people face in the context. Your brief may define the exact solution or the general directions for possible solutions to start generating ideas. It is a good idea to write a few different briefs and choose one that fits the constraints of the given design context.

Use the sheets provided for your work. Ask the researchers if you have any doubts.

Step 2: Sketch and note as many ideas as possible

Generate as many design ideas as you can. The design ideas can be for products, services, system configurations, value chains and business models. Do not discard ideas. Infeasible ideas can later be modified to make them better suited for the context.

Guidelines for designing solutions for the base of pyramid contexts are given below. These can be used as design prompts during your ideation. You can choose to design a series of ideas and use the guidelines to develop the ideas further. Or you could choose to go through the guidelines one by one and create new ideas.

Use the sheets provided for your work. Ask the researchers if you have any doubts.

Reference Sheet for Generating Design Ideas

Essential Guidelines for Designing Solutions for Base of Pyramid Contexts	
<ul style="list-style-type: none">• Products should be easy to use, affordable and durable.• Materials that can be sourced locally should be used. As far as possible sustainable material and resources should be used.• Design solutions that have simple Production methods and assembly.• Think of solutions that can be made with low skilled labour and do not use niche machines or processes.• Think about changing the core technology or the architecture of the product to reduce the cost significantly.• There should be systems that help to develop the skills of the people in context.• Solutions should be supported with novel business models and payment methods.• Reduce the cost of owning the product by using financing schemes and pay per use models.• Can a financial assistance or credit system/scheme be associated with the solution?• Design unique product identity and brand. Think of novel brand building activities which are suitable for the context.	<ul style="list-style-type: none">• What activities should be conducted in the community to build trust in the solution?• How can local cultural and social practices be integrated into the design or distribution of the solution?• Solutions should be supported through value chains that include local entities, leverage local environments and support social networks.• What are the significant constraints in the context, and how will they affect the solution?• Engaging local people, especially women, in the solutions can improve the well-being of a lot of people.• Design system configurations and value chains that help to develop the concepts in close proximity to users.• Design ways in which the social impact of the solution could be made more evident to people.• How can solution cost be reduced by leveraging economies of scale?• Think of how product design will be affected by systems, service and distribution strategies.• What role can be played by local leaders and influential persons in the development or distribution of the solution

Step 3: Review, Select and Combine Best Ideas

Review the ideas you created and select the best ones that will contribute to solving the design problem. Modify ideas as necessary and combine compatible ones into cohesive solutions. Ideas can be selected based on how well they mitigate the constraints in the context.

Use the sheets provided for your work. Ask the researchers if you have any doubts.

Step 4: Develop and Present the Final Concept

Select the best combination of ideas and develop the final concept. Use sketches, systems maps, flow charts and other visual ways of representing the overall solution. Sketch the product design concept separately.

The final concept should be presented cleanly and clearly so that expert evaluators can easily understand its functioning and supporting systems.

Use the sheets provided for your work.

Ask the researchers if you have any doubts.

Step 5: Submit your work and gather for snacks and debriefing

Now that you have completed your work, you can choose any snacks from the table. After snacks, gather for a focus group session for discussing your experience with the concept generation exercise.

Thank you for participating in this exercise.

C.2 FDC-test workbook

Workbook for Concept Generation

Step 1: Reframe the Problem statement into a Product and Services oriented statement

Rewrite the problem statement such that your statement mentions a solution that is central to fulfilling the need and has accompanying services with the product.

It is not easy to write the statement at once, so do it multiple times, without deleting or removing the ones you previously wrote. Finally, select one from the list that you created. This will be the problem statement for the rest of the worksheet.

Once you have selected the statement, review it again and remove, modify or delete words that may lead you to develop very specific ideas.

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 1 Worksheet
 Reframe the Problem statement into a Product and Services oriented statement

Write the Given Problem Statement/Design Brief:

Write The re-framed problem statements:

Iteration 1 :

Iteration 2:

Iteration 3 :

Iteration 4 :

Use Extra Sheets if required...

The Final Selected Problem Statement for further work is: Iteration # _____

Step 2: Write the requirements for the Product and Services

List down as many requirements for the product design and the Service design as possible. As far as possible, write the requirements such that they do not point towards a specific solution.

Write qualitative statements (e.g. instead of writing 'cut grass to 2cm', write 'keep grass short')

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 2 Worksheet

Write the requirements for the Product and Services

Write the requirements for the product

Write the requirements for the service

Use Extra Sheets if required...

Step 3: Generate as many ideas as possible.

Generate as many ideas as you can for the product to fulfil your problem statement. At this point, you need not think about the strategic design. We are more interested in generating ideas that will fulfil the central need.

For clarity in communication, it is essential to have at least one sketch and a short description of the idea.

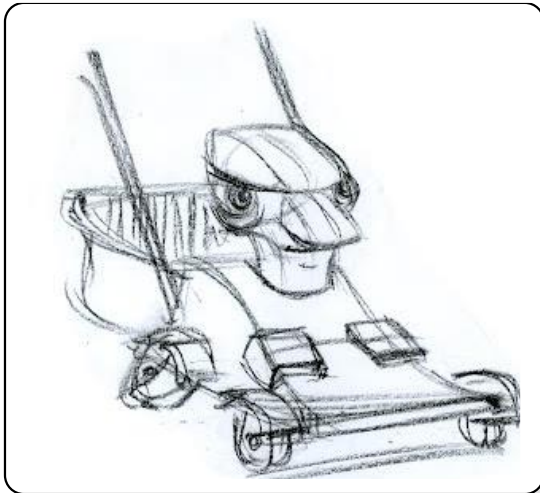
Use the following prompts to help you in generating appropriate ideas:

- Products should be easy to use, affordable and durable.
- Design solutions that have simple Production methods and assembly.

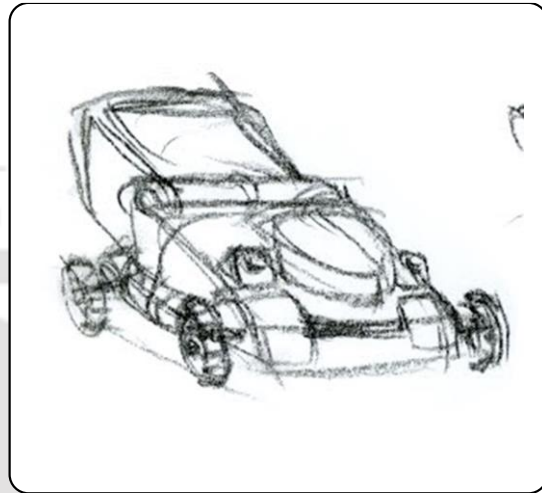
- How can local cultural and social practices be integrated into the design?

Use the space given for your work. Follow the directions of the researchers.

Example:

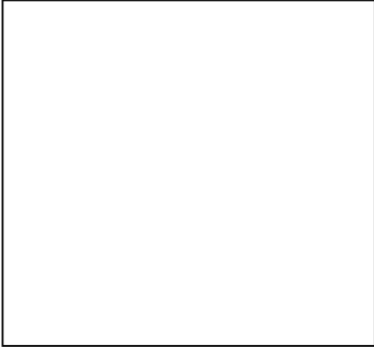
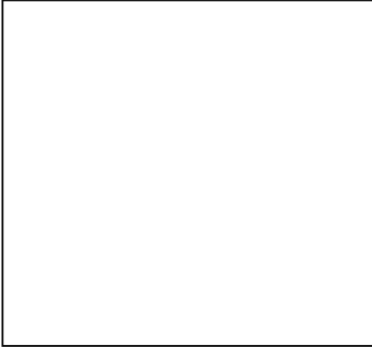




Idea 1 Description: *This idea is a lawnmower
with a collection bag at the user's end*



Idea 2 Description: *a petrol driven lawnmower
without a collection bag*

The following sheet was provided to record the outcomes of the step:

<p>Step 3 Worksheet Generate at as many ideas as possible</p>	
<p>Draw the ideas and write a short description of its working in the space provided.</p>	
	
<p><i>Description:</i> _____</p> <p>_____</p> <p>_____</p>	<p><i>Description:</i> _____</p> <p>_____</p> <p>_____</p>
	
<p><i>Description:</i> _____</p> <p>_____</p> <p>_____</p>	<p><i>Description:</i> _____</p> <p>_____</p> <p>_____</p>
<p><i>Use Extra Sheets if required...</i></p>	

Step 4: Select and combine a set of ideas and make the holistic solution

Select a set of ideas that seem promising based on your understanding of the context and combine them to form one concept. Draw this concept with as many details as possible and write a short description of how it works. Write down the solution that currently exists which is closest to your solution in the space provided.

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 4 Worksheet
 Select and combine a set of ideas and make the holistic solution

Draw the ideas and write a short description of its working in the space provided.

Description:

Closest product to your design

Use Extra Sheets if required...

Step 5: Generate a Systems configuration for the solution in use

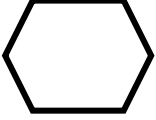


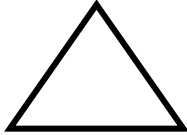



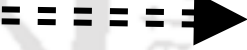
Design a systems map that depicts the interaction and configuration of products and stakeholders for the whole solution when it is in use. Keep the product(s) at the centre and the stakeholders surrounding it. Note any additional products required for the system to function (e.g., coupons, cards, kiosks, software, equipment).

Use the following prompts to help you in developing the system’s configuration:

- As far as possible, aim for accommodating local people and local entities as stakeholders.
- The aim is to design a unique and novel system that is different from the scenario of any existing products (e.g. the one you noted down in step 4)
- Incorporate systems that help to develop the skills of the people in context.

- Reduce the cost of owning the product by using financing schemes and pay per use models.
- Engaging local people, especially women, in the solutions can improve the well-being of many people
- What role can be played by local leaders and influential persons

Use the following notations when developing the systems map so that there is consistency in visual depiction:

 <p>Use for depicting <i>Tangible Artefacts</i> that does not exist yet. The things that need to be designed. These can be the allied products and the main product.</p>	 <p>Use for depicting People or Entities led by people (e.g. organisations, agencies, NGO's etc.) and The stakeholders in the system.</p>	 <p>Use for depicting Existing Tangible artefacts or Other existing products that may be required for the system to function</p>	 <p>Use for depicting tangible or intangible resources (e.g. fuel, banking facilities, vehicle, bicycle etc. except human resource)</p>
<p>Depict <i>Material Flow</i> between entities using the arrow:</p> 	<p>Depict <i>Information Flow</i> between entities using the arrow:</p> 	<p>Depict <i>Financial Flow</i> between entities using the arrow:</p> 	<p>Depict <i>Labour Flow</i> between entities using the arrow:</p> 

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 5 Worksheet
Generate a Systems configuration for the solution in use

Draw the stakeholder map when the product is in use

Primary Stakeholders
 Tertiary Stakeholders

In case you cannot accommodate all stakeholders into the same diagram, use shortened names and numberings and give the details at the back of this page.

Use Extra Sheets if required...

Step 6: Generate a product architecture diagram for the concept

Develop a product architecture diagram for your selected concept

As with problem statement redefining, product architecture diagrams cannot be done in one go. To do it effectively, develop some rough designs and then finalise one. Check if the final diagram will work with your systems configuration. Make any necessary changes.

Make a list of the Most critical sub-components in your product architecture. Remove any critical sub-components that are not an essential part of the product design.

Critical sub-components are parts that...

- ...Cannot be bought off the shelf or are not standard components.
- ...are difficult to manufacture.
- ...need some experimentation before it can function as intended.
- ...need a highly-skilled workforce to develop.
- ...need special materials or equipment to manufacture.
- ...need materials that are not easily available?

Use the space given for your work. Follow the directions of the researchers.

Examples of product architecture diagram:

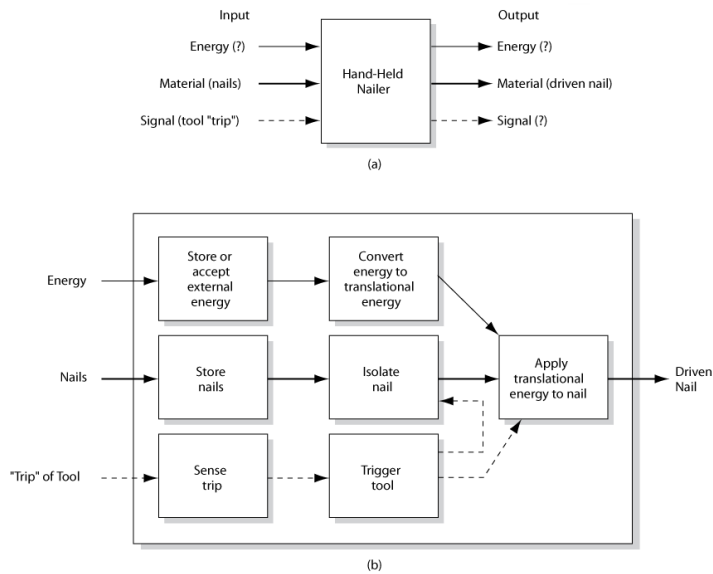


Figure i: Product Architecture Diagram for a handheld nailing gun (a hand tool used in construction)

The following sheet was provided to record the outcomes of the step:

Step 6 Worksheet
Generate a product architecture diagram for the concept

Draw the stakeholder map when the product is in use (Extra Copy)

energy input
material input
signal input

The Product

energy output
material output
signal output

energy input
material input
signal input

energy output
material output
signal output

List down the most critical sub-components

Step 8: Detail out the critical sub-components

For each critical sub-component in your product, make sketches describing how they will work and what may be the way they are embodied. Write a short description explaining your sketches.

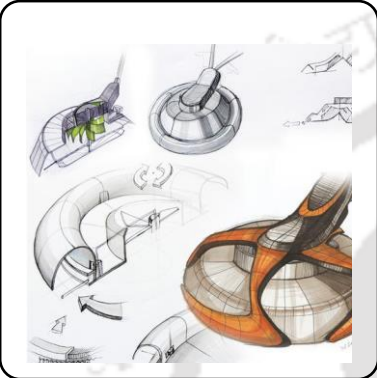
Use the following prompts to help with this step:

- Materials that can be sourced locally should be used. As far as possible sustainable materials and resources should be used.
- Design solutions that have simple Production methods and assembly.

- Think of solutions that can be made with low skilled labour and do not use niche machines or processes.
- Think about changing the core technology or the architecture of the product to reduce the cost significantly.
- How can solution costs be reduced by leveraging economies of scale?

Answer the questions in the worksheet for each of your sketches and appropriately modify critical sub-components to fulfil the requirements.

Use the space given for your work. Follow the directions of the researchers.

Example:	Details For Sub-component	Answers
	Manufacturing process	<i>Injection moulding</i>
	Majorly used material	<i>Polypropylene</i>
	Nearest place to get this material	<i>Available in Guwahati Paltan bazaar market</i>
	Nearest place to get this Made	<i>Industrial estate Amingaon, Mould needs to be made in Mumbai</i>
	Skill or knowledge required for making it	<i>Plastics manufacturing</i>
	Approximate time required	<i>About three months, including mould manufacturing</i>
	Evaluating equipment required	<i>None, visual inspection</i>
	Description of sub-component 1:	

<i>Do this for each identified critical subcomponent</i>		

The following sheet was provided to record the outcomes of the step:

Step 7 Worksheet
Detail out the critical sub-components

	Details	Answers
Description: _____	Manufacturing process	
_____	Major material used	
_____	Nearest place to get this material	
_____	Nearest place to get it Made	
_____	Skill Required?	
_____	Approx. time required	
_____	equipment required	

Use Extra Sheets if required...

Step 8: Generate the 2nd iteration of Systems configuration for the solution

Redesign the *Systems configuration* map for the holistic solution considering the details of the product architecture.

Keep the product at the centre and the stakeholders surrounding it. Add any newly identified **allied products** to the system. As far as possible, accommodate local people, local agencies and women-centric entities as stakeholders. Use the prompts and instructions given in Step 5 for help.

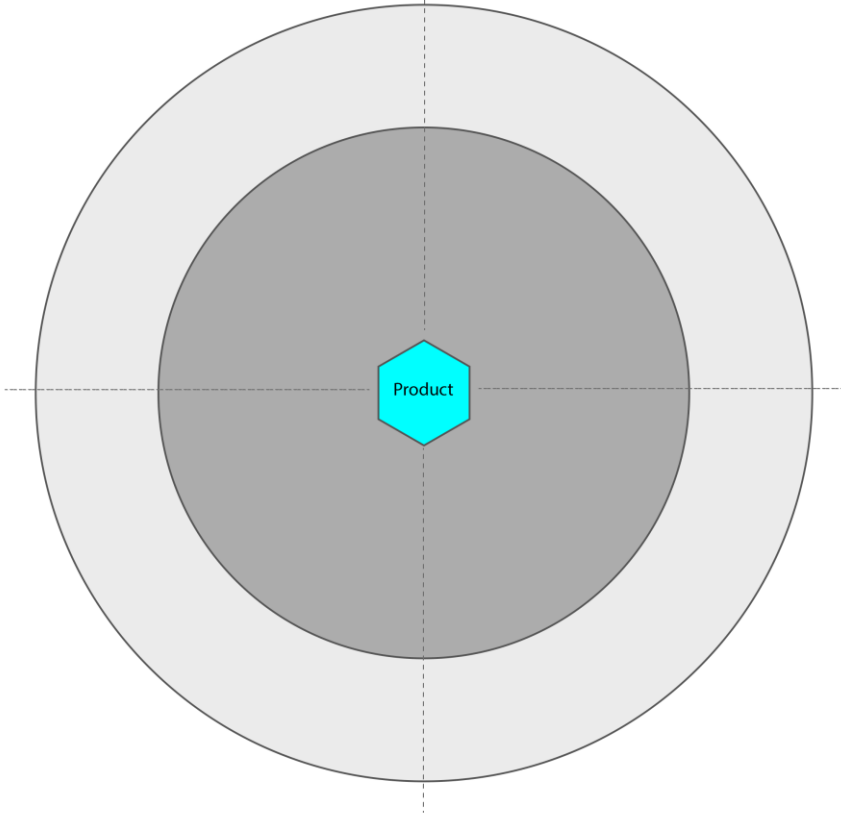
The aim is to design a unique and novel system that is better than the previously designed one.

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 8 Worksheet
Generate the 2nd iteration of Systems configuration for the solution

Draw the second iteration of the stakeholder map when the product is in use.



Legend:

- Primary Stakeholders
- Tertiary Stakeholders

In case you cannot accommodate all stakeholders into the same diagram, use shortened names and numberings and give the details at the back of this page.

Use Extra Sheets if required...

Important Instructions for next steps

The next steps include designing systems that are beyond just the 'Use' phase of the product. For effectively doing this, it is a good idea to review the problem statement you started with and note any new details that have emerged during the previous steps. These details could be a newer understanding of the system, a new requirement, a new constraint identified or removed, etc.

In the next steps, you will create a series of system maps with a **'state of the product'** at the centre, surrounded by the stakeholder's interactions

Five 'states of the product' can be defined based on its lifecycle. These are:

- **'Product being made'**: the state when the product is being manufactured. This includes the procurement of materials, the manufacturing of the parts, the assembly, the transportation of materials, the packaging, inventory and warehousing and eventual transportation.
- **'Product being disseminated'**: This is the state when the product is being transferred to its intended user. This included the transportation from inventory, dissemination, branding, promotion, transfer to the intended user, installation, commissioning, demonstration and first run of the product.
- **'Product being Used'**: In this state, the product is used as intended, fulfilling its needs. You already made this systems configuration in the previous step. It included the use of the product, the replenishment, the maintenance, the procurement of consumables, any modifications at users' end and general upkeep of the product.
- **'Obsolete product'**: The state when the product is within its usable lifetime but has been rendered obsolete since it cannot serve its function. This includes service, spare parts procurement, product or parts transportation, installation, test run, commissioning, etc.
- **'Useless product'**: The product is in such a state that it can no longer fulfil its intended or secondary needs due to limitations in its architecture which stops it from being repaired. This includes pickup of product, transportation, disassembly, reclaiming, recycling, disposal etc.

Use the prompts given in each step to help with generating the Systems maps.

Step 9: Design a Systems configuration with 'Product being made'

Design a *Systems configuration* map for the holistic solution considering the phase 'Product being made'.

Redesign the *Systems configuration* map for the holistic solution considering the details of the product architecture.

Keep the product at the center and the stakeholders surrounding it. Add any newly identified allied products to the system. As far as possible, accommodate local people, local agencies and women-centric entities as stakeholders.

Use the following prompts to help you with making the system:

- Materials that can be sourced locally should be used. As far as possible sustainable materials and resources should be used.
- There should be systems that help to develop the skills of the people in context.
- Solutions should be supported with novel business models and payment methods.
- Reduce the cost of owning the product by using financing schemes and pay per use models.
- Can a financial assistance or credit system/scheme be associated with the solution?
- How can local cultural and social practices be integrated into the design or distribution of the solution?
- Solutions should be supported through value chains that include local entities, leveraging local environments, and supporting social networks.
- What are the significant constraints in the context, and how will they affect the solution?
- Engaging local people, especially women, in the solutions can improve the well-being of many people.
- Design system configurations and value chains that help to develop the concepts near users.
- What role can be played by local leaders and influential persons in the development or distribution of the solution

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 9 Worksheet
Design a Systems configuration with 'Product being made'

Draw the stakeholder map when the product is being made. Keep 'Product being made' at the center and show the stakeholders and interactions surrounding it. Try to include as many of the stakeholders from all of previous steps as possible

■ Primary Stakeholders
■ Tertiary Stakeholders

In case you cannot accommodate all stakeholders into the same diagram, use shortened names and numberings and give the details at the back of this page.

Use Extra Sheets if required...

Step 10: Design a Systems configuration with 'Product being disseminated'

Design a systems map for the phase 'Product being Disseminated'.

Keep 'Product being disseminated' at the center and show the stakeholders and interactions surrounding it. Add any allied products that may be required for the system to function. Try to include as many of the stakeholders from all of previous steps as possible. Add new stakeholders where necessary.

Use the following prompts to help you with making the systems map:

- What training programs are needed for users and partners?
- What kind of on-field activities will build trust in the brand?
- Which existing agencies can help in the deployment of the product?
- What if a local body is set up for supporting the supply network?
- How to incorporate local culture into the distribution of the solution?
- How can locally influential personalities help in deployment?

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 10 Worksheet
Design a Systems configuration with 'Product being disseminated'

Draw the stakeholder map when the product is being disseminated. Keep 'Product being disseminated' at the center and show the stakeholders and interactions surrounding it. Try to include as many of the stakeholders from all of previous steps as possible



Primary Stakeholders

Tertiary Stakeholders

In case you cannot accommodate all stakeholders into the same diagram, use shortened names and numberings and give the details at the back of this page.

Use Extra Sheets if required...

Step 11: Design a Systems configuration with 'Obsolete product'

Design a systems map for the phase 'Obsolete product'.

Keep 'Obsolete product' at the centre and show the stakeholders and interactions surrounding it. Add any allied products that may be required for the system to function. Try to include as many of the stakeholders from all of the previous steps as possible. Add new stakeholders where necessary.

Use the following prompts to help you with making the systems map:

- How can a product-service system model be used?
- What are the significant constraints in the context, and how will they affect the solution?
- Can a financial assistance or credit system/scheme be associated with the solution?
- How can the business become an income source for people in this context?
- Can the solution be more sustainable in long term consumption?
- How can the solution support entrepreneurship in this context?

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 11 Worksheet
Design a Systems configuration with 'Obsolete product'

Draw the stakeholder map when the product is Obsolete or Broken. Keep 'Obsolete or Broken product' at the center and show the stakeholders and interactions surrounding it. Try to include as many of the stakeholders from all of previous steps as possible

■ Primary Stakeholders
■ Tertiary Stakeholders

In case you cannot accommodate all stakeholders into the same diagram, use shortened names and numberings and give the details at the back of this page.

Use Extra Sheets if required...

Step 12: Design a Systems configuration with 'Useless product'

Design a systems map for the phase 'Useless product'.

Keep 'Useless product' at the center and show the stakeholders and interactions surrounding it. Add any allied products that may be required for the system to function. Try to include as many of the stakeholders from all of the previous steps as possible. Add new stakeholders where necessary.

Use the following prompts to help you with making the systems map:

- Can the solution be more sustainable in long term consumption?
- What are the services needed for end-of life of the product?
- How will the service provider access the product after its end-of-life

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:

Step 12 Worksheet
Design a Systems configuration with 'Useless product'

Draw the stakeholder map when the product is Useless. Keep 'Useless product' at the center and show the stakeholders and interactions surrounding it. Try to include as many of the stakeholders from all of previous steps as possible

■ Primary Stakeholders
■ Tertiary Stakeholders

In case you cannot accommodate all stakeholders into the same diagram, use shortened names and numberings and give the details at the back of this page.

Use Extra Sheets if required...

Step 13: List down new ideas for product design

Based on the work done till now, list down any new ideas that may be incorporated into the product design.

These Ideas could be related to (but not limited to):

- the adding, removal or modification of any functionality in the product
- the changes to the parts, components, assembly or architecture
- modifications of constraints or requirements.
- New methods of payment and income generation
- New methods of distribution, marketing and dissemination

Use the space given for your work. Follow the directions of the researchers.

The following sheet was provided to record the outcomes of the step:



Step 13 Worksheet

List down new ideas for the product or system design

Based on the work done till now, list down any new ideas that may be incorporated into the product or system design

<i>New Ideas for Product</i>	<i>New Ideas for System</i>
List more if required...	

Use Extra Sheets if required...

Step 14: Make a flow diagram for the primary stakeholders of the system.

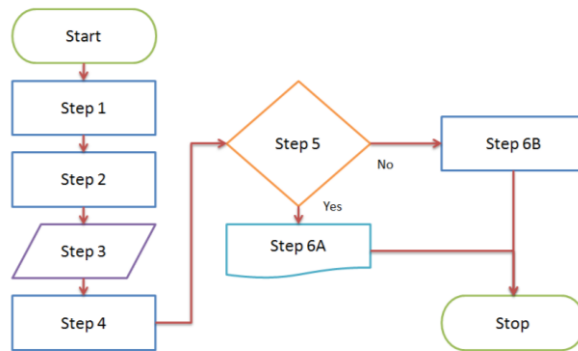
Make a flow diagram for how the primary stakeholders will use the product and interact with the system throughout its lifecycle.

Use the space given for your work.
Follow the directions of the researchers.

Example

Figure ii: A typical flow chart listing the steps. For your case, each step has to be an action that the users and stakeholders does.

The following sheet was provided to record the outcomes of the step:



Step 14 Worksheet Make a flow diagram for the primary stakeholders of the system.
For each of the primary stakeholders of the system, make a flow diagram of their actions. Use more pages if required.
<i>Use Extra Sheets if required...</i>

Step 15: Make an Offering diagram for the final proposed solution.

Make the offerings map (also called service blueprint) for the proposed solution considering the product in use. End with a brief write-up of any aspects that could not be covered in the previous steps.

Use the space given for your work. Follow the directions of the researchers.

Examples:

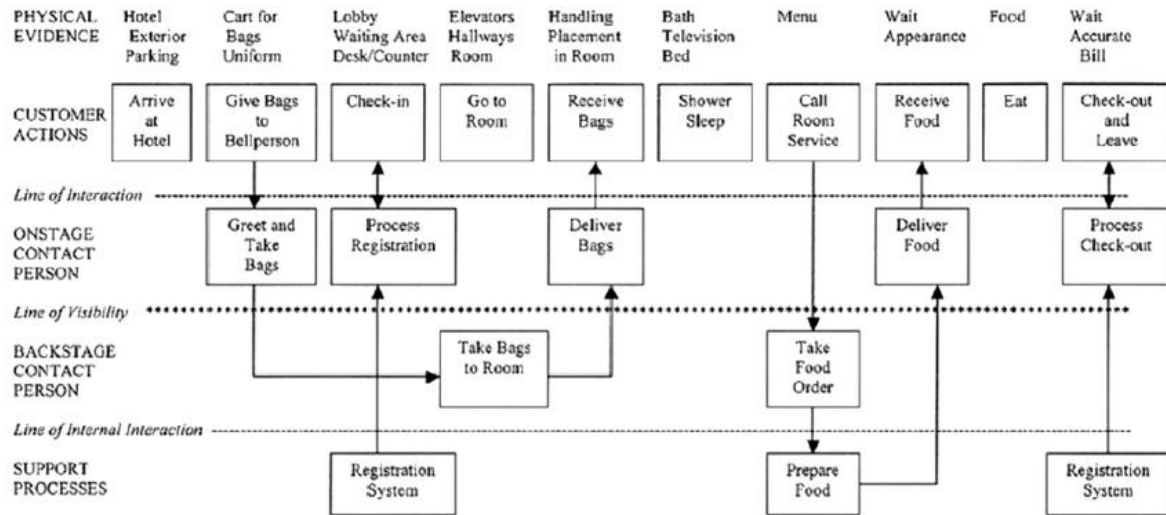


Figure iii: An Offering map for a hotel check-in service

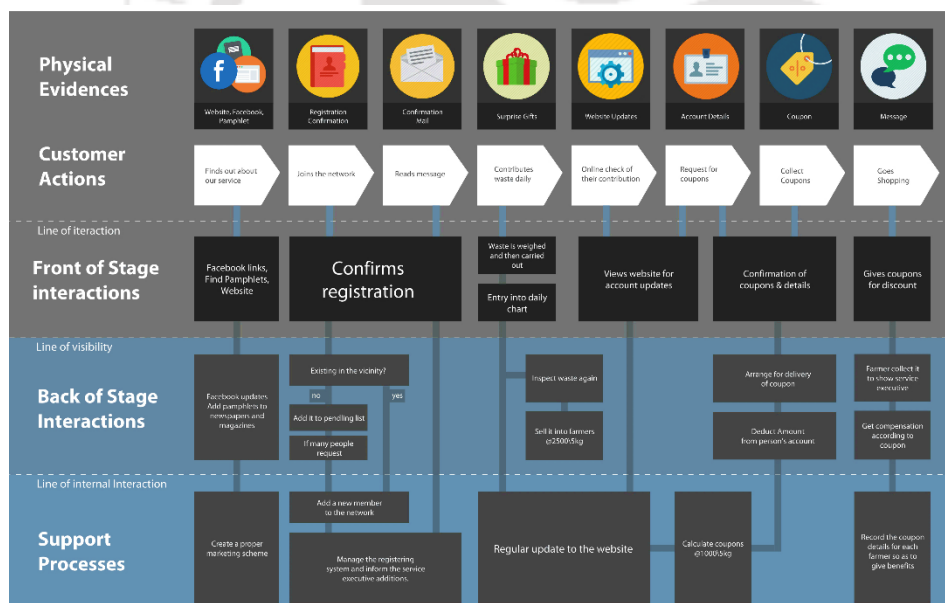


Figure iv: Service Blueprint for an online service

-X-

Appendix D – Two page summary of design concepts

A two-page summary of each concept resulting from the four design conceptualisation exercise (DCE) sessions was created to help with expert evaluation. This was done to reduce biases due to unequal sketching and writing abilities of the subjects. An illustrator was enlisted to redraw the concept sketches in a similar style on an individual page. Similarly, researchers reviewed the written material provided by the subjects and structured it on a single page. The structuring was done to highlight specific details needed for expert evaluation of the concepts. Therefore, a two-page summary for every concept was created, with one full page of sketches and another page with details. The two-page summary sheet for two of the concepts generated during the sessions is shown for illustration.



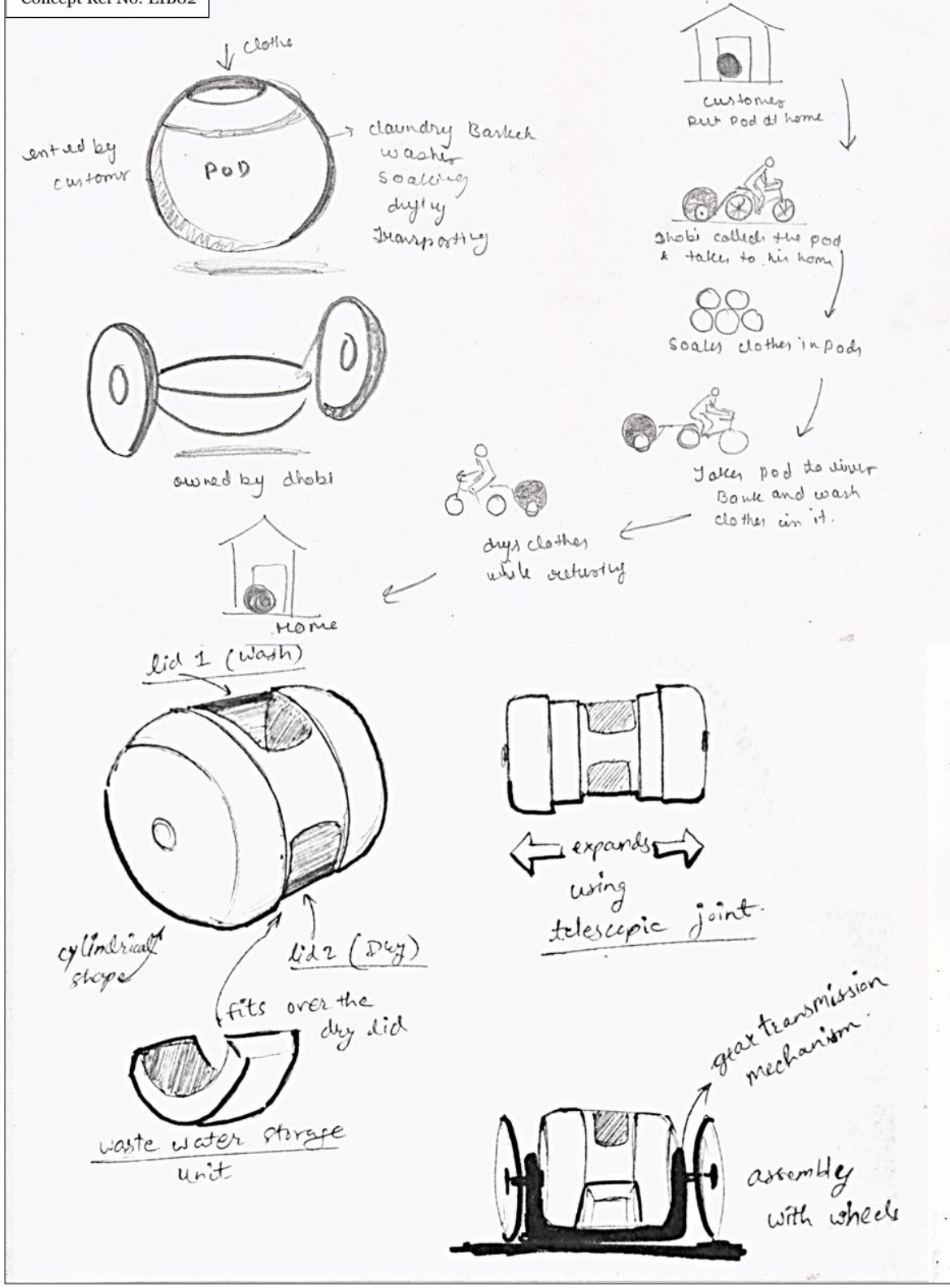


Figure D.i: Sketches page for concept numbered: EIB02

Description of the Product Concept:				
<p>The concept is a device for transporting clothes and various other activities related to washing. The device is a special container in the shape of a pod that can be attached to a bicycle using a wheeled attachment. The Dhobi gives the pod to his customers as part of the service he provides them. Customers use the pod as a laundry basket. The clothes are soaked in the pod itself. When attached to the bicycle, the pod is connected to the wheels through a geared mechanism. The mechanism creates necessary action for agitating and washing the cloths or spinning and drying them in the pod itself. Dhobi returns the pod with the washed clothes to the customer.</p>				
Details of the solution related to:				
<i>Feasibility</i>	<i>Viability</i>	<i>Desirability</i>	<i>Usability</i>	
<ul style="list-style-type: none"> The pod shape can be spherical or cylindrical, as shown. A gear transmission mechanism ensures that the required rotation speed is obtained. In the cylindrical pod setup, a telescopic mechanism ensures that the lids are closed securely. The pod is made of injection-moulded PP plastic and sheet metal. 	<ul style="list-style-type: none"> The customer rents the pod from the Dhobi and pays him monthly. The manufacturer refunds the Dhobi for any products returned. 	<ul style="list-style-type: none"> The pods are designed to be appealing to the customers as a laundry basket. The wheeled attachment for the pods can be used to transport other items. 	<ul style="list-style-type: none"> Two separate lids are provided for putting clothes for washing or cloths for drying. 	
Plan for the product lifecycle during:				
<i>Development</i>	<i>Distribution</i>	<i>Use</i>	<i>Repair</i>	<i>Disposal</i>
Pods and attachments are developed by manufacturer.	NA	Manufacturer owns the product and Dhobi leases the pods from them.	Dhobi returns pods to manufacturer for repair gets a new one for use.	The pods are returned to manufacturer for disposal. Manufacturer refunds the Dhobi for returned product.
Details of the solution related to:				
<i>Social and Environmental Conditions</i>	<i>Political and Legal Conditions</i>	<i>Production and Distribution Conditions</i>	<i>Income and Well-being Conditions</i>	
<ul style="list-style-type: none"> NA 	<ul style="list-style-type: none"> NA 	Manufacturer makes the product with help of appropriate OEMs.	<ul style="list-style-type: none"> Dhobi leases the pods from the manufacturer for an extended time. Dhobi only owns the wheeled attachment for the pods. 	
Stakeholders integrated into the solution			List of additional supporting products	
<ul style="list-style-type: none"> NA 			<ul style="list-style-type: none"> Bicycle. 	
Any Additional Information about the solution				
<ul style="list-style-type: none"> NA 				

Figure D.ii: The description page for concept number: EIB02

Concept Ref No: CGA03

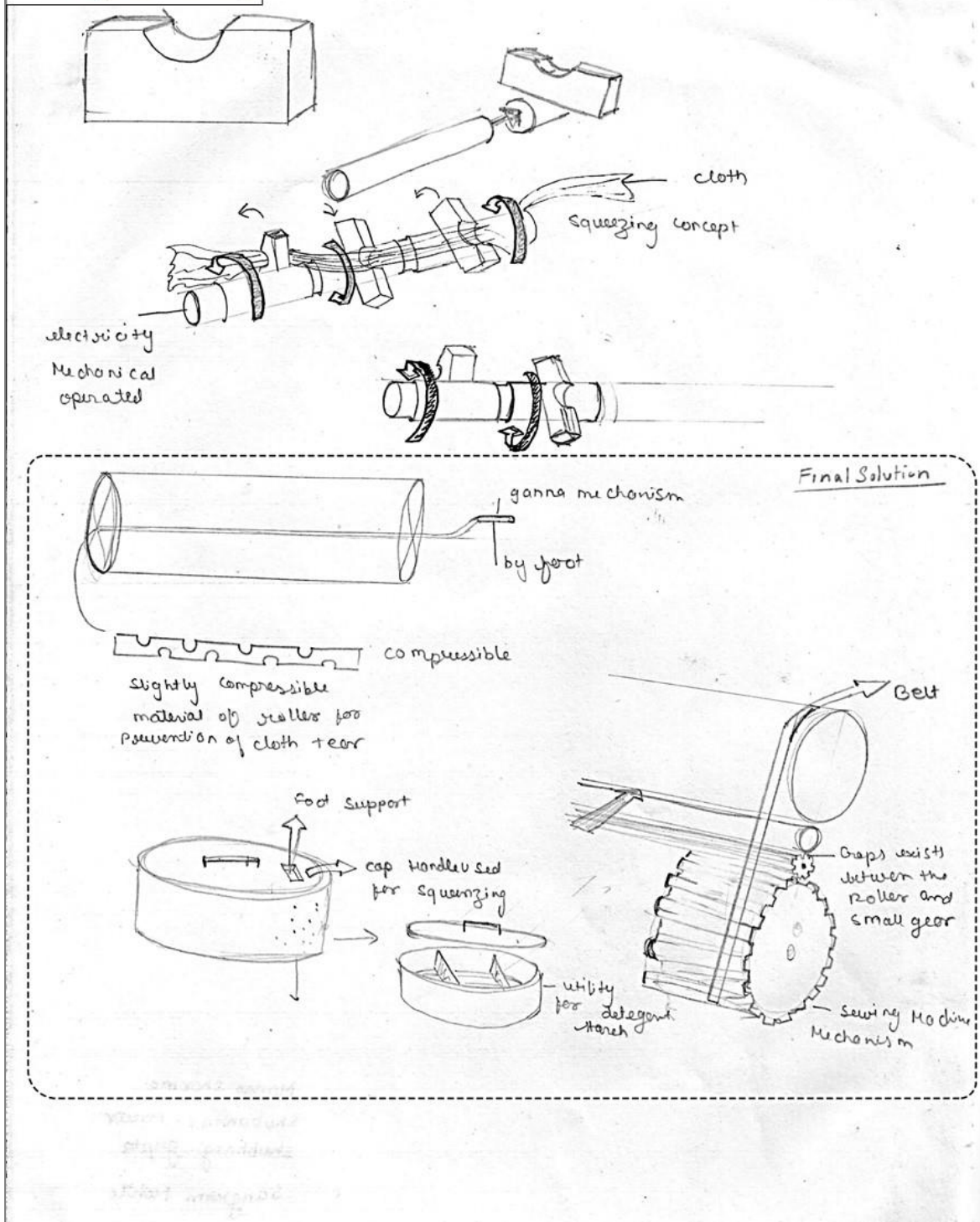


Figure D.iii: Sketches page for concept numbered: CGA03

Description of the Product Concept:				
<ul style="list-style-type: none"> • Three concepts are presented for squeezing excess water from cloths, of which two together make up the final solution. One of the devices of the final solution is a roller press which works like a sugarcane juicer. The other device is a container that can be pressed to expel water. • The sugarcane juicer type of device contains multiple rollers which press the cloths as they roll, thus expelling water. A sewing machine like mechanism is used to drive the two rollers. The roller drums are covered with a specially shaped compressible material to protect the clothes. • The foot-operated pressing device is shaped like a drum where foot pressure squeezes excess water from cloths. It can be used for smaller sized clothes. This drum also contains a space for carrying detergent and other items. 				
Details of the solution related to:				
<i>Feasibility</i>	<i>Viability</i>	<i>Desirability</i>	<i>Usability</i>	
<ul style="list-style-type: none"> • The first presented concept is difficult to manufacture hence rejected. • The roller press is covered with a rubbery material with the shown cross-section. • Roller press is driven with pulleys and belts and uses a sewing machine mechanism 	<ul style="list-style-type: none"> • The foot-operated container may have increased costs since there is an airtight compartment to carry detergent 	<ul style="list-style-type: none"> • The gear and belt mechanism for the roller press is easy to install since users are familiar with pulleys and bicycle chain 	<ul style="list-style-type: none"> • The roller press is similar to a sugarcane juicer in operation • The roller press is operated by foot • The foot-operated press is portable • Foot-operated press doubles as a storage compartment for detergents etc. 	
Plan for the product lifecycle during (system-level support for the stage)				
<i>Development</i>	<i>Distribution</i>	<i>Use</i>	<i>Repair</i>	<i>Disposal</i>
NA	NA	NA	NA	NA
Details of the solution related to:				
<i>Social and Environmental Conditions</i>	<i>Political and Legal Conditions</i>	<i>Production and Distribution Conditions</i>	<i>Income and Well-being Conditions</i>	
NA	NA	NA	NA	
Stakeholders integrated into the solution		List of additional supporting products		
The Washermen		A structure at the river bank for installing the roller press.		
Any Additional Information about the solution				
If the roller press is driven electrically then may lead to mishaps when used near a water source.				

Figure D.iv: The description page for concept number CGA03




Appendix E –Subject and Expert Briefing Details

A structured briefing and presentation were developed for providing a detailed understanding of the marginal context (MC) to the subjects during the design conceptualisation exercise (DCE) (See Section 5.2). The MC was derived from the extensive research done when designing a bicycle mounted clothes carrier for the washermen community in Guwahati (See Section 3.5). Two presentations were developed; the first one provided the necessary information about the MC to the subjects before starting the DCE sessions. The presentation contained relevant textual data, photographs with explanations and videos of various processes.

The second presentation was developed to brief the experts before they started the evaluation of the design concepts. This presentation was in the form of a 12-minute video with slides, photographs and images. The video provided details regarding the context and how the evaluation was to be conducted (see section 5.2.3). A script for the video was developed to ensure all experts were given the same information in a structured manner. The script for the video is shown after the tables.

The following tables show a few selected slides from the various presentation to illustrate the information provided during these two briefings.

Table E.1: Selected slides from the presentation briefing made to subjects before starting the conceptualisation exercise.

<p>Understanding Dhobis & Dhobighats</p> 	<p>Guwahati – An Overview</p> <p>The study was conducted at 4 different locations – Buthnath, Machkhowa, Fancy bazaar and Uzan Bazaar – at river bank of Brahmaputra in Guwahati.</p> <p>The study was divided into two major segments – structured group of Dhobis and unstructured group of Dhobis.</p> <p>In next section, we present washing process followed by opportunity areas of both – structured and unstructured group of Dhobis</p> 																					
 <p>unstructured group – Individual dhobis where every dhobi possibly could have different process/material/business model/location and pattern of working</p>	<p>Opportunity Areas - Methodology</p> <p>For this project, the problems are categorized for (i) increase in efficiency and productivity (ii) energy conservation (iii) speeding up the process and enhancement in production and (iv) where only specific step washing process is impacted</p> <p>Based on inferences identified from value chain analysis, few opportunity areas are proposed in this report. The opportunity areas presented here are independent for structured and unstructured Dhobi communities due to different needs and behaviors. Some of the opportunity areas are purposefully kept open in order to demonstrate areas those could be relevant to stakeholders beyond washing communities.</p> <p>The opportunity areas presented in this report have specific focus on efficiency, efforts & environmental hazards which are identified as high priority in value chain analysis</p> <table border="1"> <thead> <tr> <th>Impact to</th> <th>Process time</th> <th>Process time</th> <th>Efficiency</th> <th>Effort</th> <th>Effort</th> <th>Health Hazard/ Environment hazard/ Safety</th> </tr> <tr> <th>1</th> <th>2</th> <th>3</th> <th>4</th> <th>5</th> <th>6</th> <th>7</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>2</td> <td>3</td> <td>4</td> <td>5</td> <td>6</td> <td>7</td> </tr> </tbody> </table>	Impact to	Process time	Process time	Efficiency	Effort	Effort	Health Hazard/ Environment hazard/ Safety	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Impact to	Process time	Process time	Efficiency	Effort	Effort	Health Hazard/ Environment hazard/ Safety																
1	2	3	4	5	6	7																
1	2	3	4	5	6	7																

Unstructured Group of Dhobis

Washing process of unstructured group of Dhobis

View to the Brahmaputra bank. Cloths are washed at the river bank.

Dhobi's getting their clothes to the riverside for washing.

Washables kept near Dhobi's preferred washing area.

Soaked clothes are brushed after putting soap on stains.

Unstructured Group of Dhobis

Washing process of unstructured group of Dhobis

The washed linens are thrown over to a specific area.

Dhobi packing the wet clothes in a sack for transportation.

Few Dhobis (who live in close vicinity) prefer the river bank for drying.

The sack after being loaded on the preferred medium – mostly bicycles or human cart

Opportunity Areas - Soaking

Soaking demands Dhobis to soak the wet cloths by feet in a container. The wet cloths are combination of water, detergent and soda which potentially impacts health of Dhobis.

Three following opportunity areas emerge here

- Design intervention to reduce the manual effort needed to soak wet cloths. The intervention must also reduce the human body contact with chemically affected water.
- Propose a new method or a new detergent that eliminates the need to soak the cloth prior to washing. This will not only reduce the human efforts and health, but also save water and reduce water pollution

Wet cloths being soaked inside a container. The wet cloths are combination of water, detergent and soda

Infected feet of Dhobis due to constant body contact with chemically affected water

Opportunity Areas – Easy, efficient, human-environment healthy washing & rinsing

Rinsing and Brushing the cloths during washing is performed multiple times by Dhobis. However, this process is performed in traditional manner which demands extreme manual efforts, have poor ergonomics and possibility to damage cloths. Moreover, continuous contact to chemically influenced water damages the health and river water.

Brushing is done through placing the cloth on wooden slats placed across two corners of washing tub, followed by applying detergent to specific stains and brushing it

The cloths are rinsed in detergent water, and then relatively clean water. They are further hit on the stone to remove detergents from the water

Opportunity Areas – Packaging and Carrying cloths

Packing the wet cloths from the river bank requires additional support and has been experienced tiresome by Dhobis. The packed cloths are further transported through multiple channels – bicycle, walking or sometimes cart to transfer cloths from river bank to Dhobi's home or work place. Dhobis experience additional physical effort and balancing problems which leads to dirt and damage of cloths along with extra time consumptions

soaking

STEP	FINDINGS			BENEFIT	PROBLEMS
	Positive	Negative	Neutral		
UNPACKED clothes are taken in a container and detergent (Dish washing soda) (3 hands full) is added in water.	Loosening up of particles of stains on clothes and fabric less hot water is allowed. Clothes which were more are soaked in morning just before washing.	Less result of soaking leads to lesser use of fabric leads to wear and tear of clothes.		So that the stains are get loose down in that particular area and washing also become easier.	Proportions are to make proper while doing soaking process or else it harms their hands.
Rinse the clothes by feet	Saves time and takes less effort for the same work if done by hands.	Harms their feet as chemicals are added and they already remain in water for long time.		To save time and work faster	Chemical use and rinsing by feet harm their feet.
THE SOAKED clothes which are soaked well they before to bank is washing only.	As one soaked on previous day after they need to soak at bank of river or it becomes difficult in washing.			To save time and let washing easier as stains become loose in fabric.	They've less working space for soaking at their place.

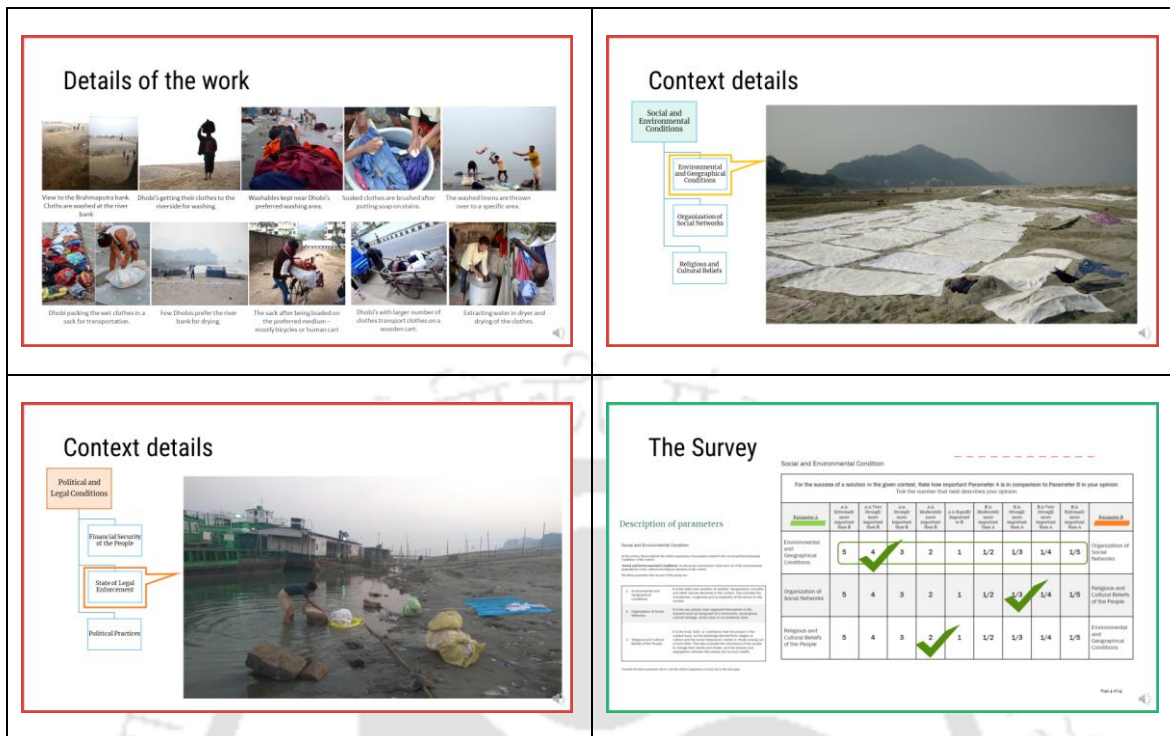
Table 2: Selected screens from the video presentation made for experts to help with evaluating the concepts.

Hello and Welcome.

Thank you for helping us conduct this research.

My Name is Pankaj Upadhyay.

Our friendly neighborhood Dhobi



E.1 Script for the video shown to experts

Slide 1: Hello and welcome:

Thank you for being part of this research and sharing your valuable time with us. My Name is Pankaj Upadhyay. My colleagues and I are doing this research at IIT Guwhati, Department of design. For your effective participation, I have to let you know a few details through this presentation. So let's start.

Slide 2: What the is research about: Bottom of the pyramid.

First and foremost, a little background. In this research, we are trying to understand how designers can design better products and services for the 'base of the pyramid'. The term 'base of the pyramid' or BOP originates from a famous diagram that maps the global population against income. We use the term more broadly to refer to the world population who live in poor socio-economic conditions.

Slide 3: What the is research about: Aspects of poor socio-economic conditions

Poor socio-economic conditions may be reflected by low income, low literacy, unequal rights, lack of access to common facilities and unequal capabilities, amongst other things. We want to understand how solutions can be designed for people living with such constraints. From our initial studies, we have found that the process of designing such products and services is very different from the typical process. This is where we need your help.

Slide 4: Our goal: Factors

We have identified you as an expert on designing solutions for the base of the pyramid. Our specific interest is to understand which of the factors you consider as important when designing for the BoP. We will ask you to weigh a set of parameters based on which we can calculate their relative importance. With this information, we intend to train novice designers to design better solutions for the context.

Slide 5 and 6: Our goal: Evaluate the solutions

Moreover, this research also attempts to evaluate how experts would score design concepts against some

parameters. At the end of this exercise, you will be presented with concepts of products which you will grade against certain parameters on a 10 point scale.

Slide 7: Things to consider

In the next few slides, we will present to you in detail the life, work and living environment of the dhobi community in India. We will call this the 'design context' or 'context' in short. As you know, in India, the people who provide the service of washing clothes to households and businesses are called the dhobis. We can also call them the washermen community.

Slide 8: Our friendly neighbourhood dhobi.

Members of the dhobi community-run micro businesses of washing and ironing. A large portion of their work is unstructured and without established storefronts or formal business processes. They provide essential services to almost all parts of semi-urban and urban areas in India. They are generally socioeconomically underprivileged and are part of the BoP population. Around 40% of washermen live in cities and provide services to hotels, hospitals, tent houses, railways, government establishments as well as households.

We studied the washermen community spread across Guwahati, Assam to Understanding the context, environment and processes involved. We found that a majority of the people work in an unorganised manner and have age-old working methods which require intense physical labour. They cannot afford modern machines, products or services that might solve their problem.

Slide 9: Some more details

At most places, they use rivers and lakes to wash and rinse the cloths. Although this is unsustainable, due to lack of infrastructure and poor enforcement, this is the only way they get access to water. Many of them work collectively and share their profits. They wash more than 200 clothes a day and use thelas and their personal bicycles for transportation. Customers are acquired through word of mouth within an agreed-upon territory. They earn anywhere between Rs 50 a day to Rs 500 a day on average, depending on seasons and other factors. Due to exposure to detergents and other chemicals, they face a lot of skin problems in their occupation.

Slide 10: Details of work: generic details

Here we present to you the details of their typical workday. The Dhobis arrive at the riverbank early morning at 4:30 am and continue working till about 11:00 am. In Guwahati, a number of Dhobis we spoke with use the river bank. As you can see, the terrain is uneven and sandy. This restricts the entry of vehicles up to their working area. They transport the clothes in bundles by carrying them on their head or on cycles. This takes a lot of effort. Prior to coming to the riverfront, the clothes are soaked overnight to loosen the dirt on the fabric. They wash, rinse, collect and pack the washed clothes by 11:00 am. Before washing, they lay down their clothes in a linear fashion and carry on with the rinsing and beating one by one. During the process, the Dhobis segregate the clothes so that the colour does not bleed. However, this can never be entirely eliminated. Some fabrics which have hard stains, such as jeans and shirt collars, are brushed and soaked in other chemicals. They use specialised brushes with jute bristles, wooden planks and large aluminium tubs for scrubbing the clothes. The chemicals used by them include soda ash, caustic soda, bleach, fabric softeners, perfumes and dyes. Once the necessary pre-processes are done, the clothes are rinsed in the river and squeezed to remove excess water. These are then thrown on a large bedsheet where they are collected. After the entire load is completely washed, the large bed sheet is used to pack up the clothes into a bundle. Some Dhobis also use the riverbed to dry their clothes. But most of the transport of the wet bundles their shops or home for drying and ironing. These bundles sometimes reach a weight of up to 80 Kgs. Sometimes hand carts are used for transportation, whose cost is shared by the Dhobis. Back home, they dry their clothes in the sun. Some Dhobis have access to centrifuge driers which cuts their process time. However, these machines are rudimentary in nature and highly unsafe in operation.

Slide 11: Evaluation Hierarchy and Parameters

Based on our initial research, we have identified some parameters of good design for the BoP. We have grouped these parameters in a hierarchical fashion. The chart shows that there is 14 Parameter that affects the success of a solution in marginal contexts. These parameters are grouped under four

primary factors: Social, Cultural and Environmental Conditions, Security, Legal and Political Conditions, Access to Markets and Resources and Affordability, Well-being and Literacy Conditions.

We will refer to this chart as the Evaluation hierarchy And each element within it as the parameters. Each of these parameters will help us evaluate the design concepts. We will describe each of them in a moment. For the time being, let us understand the context from the perspective of these parameters.

Slide 12: Description of context based on CEH

There are three parameters grouped within the 'Social and Environmental Conditions' We will take a look at the context from the perspective of each of these parameters. Considering the Environmental and Geographical Conditions, we see that the majority of work is carried out on the river banks and during early mornings. The river banks have fine white sand, which is wet, and do not allow for vehicles to reach the river. The temperature during work hours varies from 27 degrees in summer to 3 degrees in the winter. Dhobis in Guwahati have a close-knit community among them since they mostly belong to Bihar and Uttar Pradesh. Some of them have families with up to two children and wives who works as a housemaid. There are associations with groups of washermen around individual dhobi ghats. The primary reasons for the formation of these communities are, Working on social issues, Approaching the authorities for approvals, Municipal corporation funding etc.

Slide 13: Continued...

Religious and Cultural Beliefs: Most of the washermen are Hindu or Muslim. We found no other religious groups in the sample we studied. Since they are immigrants from neighbouring states, they share similar cultural practices and beliefs.

Slide 14: Political and Legal Conditions

Considering the Political and Legal Conditions parameters, we see that they are not Banked, do not have health or life insurance, and mostly earn and spend in cash. Financial Institutions are reluctant to provide them with services due to a lack of established credit. However, They do receive credit from local shops and establishments where they are regulars. Since they are part of an immigrant community and use the open rivers to clean their clothes, they are sometimes harassed by the authorities. Some of them spend the night in park benches and shop fronts for which they have to bribe the local police. Local community leaders protect the people who have a place to stay there. Many political parties consider them as a vote bank and thus try to placate them during election times.

Slide 15: Production and Distribution conditions.

The Third group is related to the production and distribution conditions. These five parameters describe the nature of facilities and infrastructure in the context that can support a design solution. Guwahati is a semi metropolitan city and has some industrial areas which can provide manufacturing facilities. It has fairly good roadways for transportation and good access to electricity and fuel. Most raw materials can be procured in Guwahati. Specialised materials may be difficult to procure, in which case the nearest metro city is Kolkata. Several different educational institutions in Guwahati can provide manpower for production, manufacturing and sale. Most marketplaces are accessible to both the producers as well as the Dhobis in Guwahati.

Slide 16: Income and Well-being Conditions.

There is a significant wage gap amongst the Dhobis. Smaller and newer members may make up to 3000 Rupees per month, whereas more established people may make up to 15000 Rupees per month. Sometimes a team of dhobis work together to execute an order and share the profits. A significant amount of daily earned wages are utilised towards daily necessities. A lot of them spend a large portion of their income on tobacco and alcohol. Some of them have families to whom they send a portion of their monthly earnings. Their work requires them to use harsh chemicals, due to which their hands and feet get damaged. Since they consider this as part of their occupation, they have a casual attitude towards such ailments. A significant portion of washermen is not educated beyond primary schools. In our sample, almost no one has graduated 10th standard. However, those who have children make sure that they attend school. Unfortunately, other researchers point out that the children drop out before completing secondary school.

Slide 17: Conclusion

We hope you have a decent understanding of the environment, life and surroundings of the dhobis. A lot of information is not covered in this presentation, and we rely on your expertise and prior experience to fill in the gaps. We assume that you can form a picture of the life of the Dhobis with the little information we gave you. We have designed a survey to measure the relative importance of the parameters in the Evaluation hierarchy based on your understanding of the context. With this, we will understand what aspects of the designed solution you will value more for the given context.

Slide 18: Questionnaire

If you review the survey questionnaire, you will see the first few pages has the introductory questions and basic information. On the fourth page, you are presented with the first set of rating questions. The description of each of the parameters and the scale of evaluation is presented before the start of each set of questions. In each rating question, Please indicate the relative importance of parameter A compared to parameter B, considering the context. The numbers indicate the value given to the relative importance between the parameters. You can indicate your response by Ticking or Crossing the appropriate number in the box

Slide 19: Thank you

Now that you have all the information necessary for completing the survey, please review all the pages and answer the questions. Once again, we would like to extend our gratitude for helping us with this research. Thank you.

-X-

Appendix F – AHP Questionnaire

The following questionnaire was presented to experts for finding the weights of the various CEH parameters as part of the rough-group Analytical Hierarchy Process (AHP). Details about the questionnaire can be found in Section 5.2.4.

AHP Questionnaire to understand the relative importance of parameters in Design for Marginal Contexts

Thank you for considering our request to be part of this research. We are conducting this survey to understand how designers can design good solutions for the socioeconomically underprivileged people in our world. Here we refer to this population as the Base of Economic Pyramid or 'BoP' in short.

This exercise will take you about 20 minutes to complete.

As part of this survey we may collect some personal information from you, like Name, Age, Email address etc. This information will make it easy for us to analyze the collected data.

The information you provide will be used only for the purposes of this research and will not be disclosed in any manner that is personally identifiable.

Please answer the questions below and continue to the next page.

Name:							
Email ID: (This will be used for any future communications and clarifications only)							
Age Group:							
Please tick one	18 to 24 Years	25 to 34 Years	35 to 44 Years	45 to 54 Years	55 to 64 Years	65 to 74 Years	75 Years or above

Which city do you work in?	
Your total years of work experience?	
Your work experience on projects related to BoP?	
How many projects related to BoP you have done?	
How many of your projects related to BoP have been marketed and sold?	
How many of your BoP projects have been prototyped or tested?	

Basic Survey Information

This is a survey for assessing the '**relative importance**' of a set of '**parameters**' which have been found to contribute to the '**success**' of a '**solution**' in a given '**context**'.

'**Relative importance**' is a number denoting the significance that something has over another. This is a number is based on your opinion of how important you find one '**parameter**' over another on a scale ranging from 9 to 1/9, where 9 is most important and 1/9 is least important.

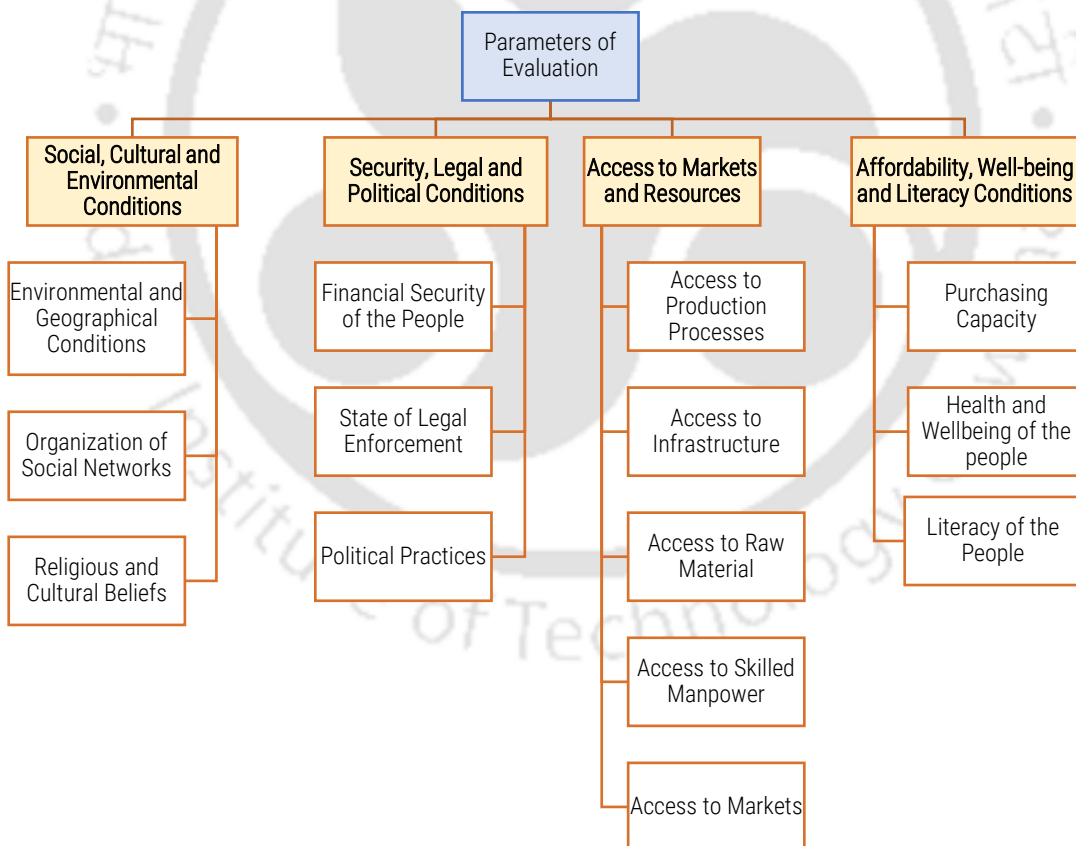
'**Parameters**' are a set of attributes that have been found to have some effect on the topic being studied.

'**Success**' is the ability of a '**solution**' to fulfill a need, or solve a problem which it intends to.

'**Solution**' is an idea, scheme or a combination of these, which has been proposed to solve a problem or fulfill a need in the '**context**'

'**Context**' is a circumstance, setting or a scenario, in which there is a problem to be solved or a need to be fulfilled. The details of the context has been explained in the accompanying video.

A total of 14 parameters have been identified which contribute to the success of the solution in BoP. These parameters are grouped and arranged in a hierarchical manner as shown below.



Social, Cultural and Environmental Conditions

In this section, Please indicate the relative importance of parameters related to the 'Social, Cultural and Environmental Conditions' of the context.

'**Social, Cultural and Environmental Conditions**' are the group of parameters which arise out of the environmental, geographical, social, cultural and religious situations in the context.

The three parameters that are part of this group are:

Environmental and Geographical Conditions	It is the state and variation of weather, temperature, humidity and other natural elements in the context. This includes the remoteness, roughness and accessibility of the terrain in the context.
Organization of Social Networks	It is the way people have organized themselves in the scenario such as being part of a community, social group, cultural heritage, social class or occupational class.
Religious and Cultural Beliefs of the People	It is the trust, faith, or confidence that the people in the context have, on the teachings derived from religion or culture and the social behaviours, habits or rituals arising out of such faith. This also includes the reluctance of the people to change their habits and rituals, and the division and segregation between the people due to such beliefs.

Consider the three parameter above, rate the relative importance of each one in the table below.

How important is 'Parameter A' in comparison to 'Parameter B' for evaluating the success of a solution to the given problems in the context? Tick the number that best describes your opinion.										
Parameter A	A is Extremely more important than B	A is Very Strongly more important than B	A is Strongly more important than B	A is Moderately more important than B	A is Equally important to B	B is Moderately more important than A	B is Strongly more important than A	B is Very Strongly more important than A	B is Extremely more important than A	Parameter B
Environmental and Geographical Conditions	9	7	5	3	1	3	5	7	9	Organization of Social Networks
Organization of Social Networks	9	7	5	3	1	3	5	7	9	Religious and Cultural Beliefs of the People
Religious and Cultural Beliefs of the People	9	7	5	3	1	3	5	7	9	Environmental and Geographical Conditions

Security, Legal and Political Conditions

In this section, Please indicate the relative importance of parameters related to the 'Security, Legal and Political Conditions' of the context.

'**Security, Legal and Political Conditions**' are the group of parameters which arise out of the state of law enforcement, governance, financial security, social vulnerability, political structure and civic rights in the context.

The three parameters in the group are:

Financial Security of the People	The ability of the people in the scenario to avail services from financial institutions (for example credit, loan, insurance).
State of Legal Enforcement	The state of law and order which people face in the scenario. This includes the strength of the government institutions in enforcing security, state and strength of intellectual property rights and vulnerability of the people to institutional corruption.
Political Practices	The influence and effect of political ideologies on the people. This includes the influence of politicians and community leaders on the people, the state of bureaucratic practices in the public institutions, state of civil rights, and the reliability of publicly available information.

Consider the three parameter above, rate the relative importance of each one in the next table.

How important is 'Parameter A' in comparison to 'Parameter B' for evaluating the success of a solution to the given problems in the context? Tick the number that best describes your opinion.										
Parameter A	A is Extremely more important than B	A is Very Strongly more important than B	A is Strongly more important than B	A is Moderately more important than B	A is Equally Important to B	B is Moderately more important than A	B is Strongly more important than A	B is Very Strongly more important than A	B is Extremely more important than A	Parameter B
Financial Security of the People	9	7	5	3	1	3	5	7	9	State of Legal Enforcement
State of Legal Enforcement	9	7	5	3	1	3	5	7	9	Political Practices
Political Practices	9	7	5	3	1	3	5	7	9	Financial Security of the People

Access to Markets and Resources

In this section, Please indicate the relative importance of parameters related to the 'Access to Markets and Resources' of the context.

'Access to Markets and Resources' are the group of parameters which are related to the difficulty faced by the designer or the solution provider, in accessing various forms of tangible and intangible infrastructure in the context such as manufacturing processes, Roadways, raw material, skilled labour etc. The five parameters in the group are:

Access to Production Processes	The ability of the solution provider to find and utilize the required development, production and manufacturing processes in the scenario. This includes the ability of the solution provider to produce in the local vicinity with the local people using sustainable means.
Access to Infrastructure	The ability of solution providers to use the infrastructure in the scenario. Infrastructure includes access to built environment (such as roads, buildings, and spaces), transportation and storage systems (such as vehicles, refrigeration, HVAC) and Energy systems (such as electricity and fuel).
Access to Raw Material	The ability of the solution provider to find, utilize and source raw materials for manufacturing and production of the solution. This includes the availability of the suppliers and distributors of materials within a reasonable vicinity of the scenario and the availability of the raw materials with these suppliers.
Access to Skilled Manpower	Ability of the solution provider in finding, recruiting and involving skilled manpower within a reasonable vicinity of the scenario with fair practices. This includes the availability of skilled manpower for development, manufacturing and distribution.
Access to Markets	The ability of the solution provider to engage with the market in the scenario and provide the solutions to the intended users through fair practice. This includes the ability of the users to access the marketplace.

Consider the five parameter above, rate the relative importance of each one in the next two tables.

How important is 'Parameter A' in comparison to 'Parameter B' for evaluating the success of a solution to the given problems in the context?
Tick the number that best describes your opinion.

Parameter A	A is Extremely more important than B	A is Very Strongly more important than B	A is Strongly more important than B	A is Moderately more important than B	A is Equally Important to B	B is Moderately more important than A	B is Strongly more important than A	B is Very Strongly more important than A	B is Extremely more important than A	Parameter B
Access to Production Processes	9	7	5	3	1	3	5	7	9	Access to Infrastructure
Access to Production Processes	9	7	5	3	1	3	5	7	9	Access to Raw Material
Access to Production Processes	9	7	5	3	1	3	5	7	9	Access to Skilled Manpower
Access to Production Processes	9	7	5	3	1	3	5	7	9	Access to Markets
Access to Infrastructure	9	7	5	3	1	3	5	7	9	Access to Raw Materials

How important is 'Parameter A' in comparison to 'Parameter B' for evaluating the success of a solution to the given problems in the context?
Tick the number that best describes your opinion.

Parameter A	A is Extremely more important than B	A is Very Strongly more important than B	A is Strongly more important than B	A is Moderately more important than B	A is Equally Important to B	B is Moderately more important than A	B is Strongly more important than A	B is Very Strongly more important than A	B is Extremely more important than A	Parameter B
Access to Infrastructure	9	7	5	3	1	3	5	7	9	Access to Skilled Manpower
Access to Infrastructure	9	7	5	3	1	3	5	7	9	Access to Markets
Access to Raw Material	9	7	5	3	1	3	5	7	9	Access to Skilled Manpower
Access to Raw Material	9	7	5	3	1	3	5	7	9	Access to Markets
Access to Skilled Manpower	9	7	5	3	1	3	5	7	9	Access to Markets

Affordability, Well-being and Literacy Conditions

In this section, Please indicate the relative importance of parameters related to the 'Affordability, Well-being and Literacy Conditions' of the context.

'Affordability, Well-being and Literacy Conditions' are the group of parameters related to the inherent capability of the people, to effectively engage with the solutions provided due to their health, well being, literacy or affordability.

The three parameters that are part of this group are:

Purchasing Capacity	The ability of the people in the context to buy and own a solution. This includes their ability to pay money for the ownership of the product, the running costs, the cost of repairs and the cost of disposal of the solution.
Health and Wellbeing of the people	The physical and mental health condition of the people in the scenario, their vulnerability to preventable diseases and access to healthcare.
Literacy of the People	The level of Literacy, Access to Education, Educational Qualification, Numeracy Skills, Reading and Writing Skills of the people. This includes the ability of the people to understand and use the solutions, and use them for intended purposes only.

Consider the three parameter above, rate the relative importance of each one in the next table.

How important is 'Parameter A' in comparison to 'Parameter B' for evaluating the success of a solution to the given problems in the context? Tick the number that best describes your opinion.										
Parameter A	A is Extremely more important than B	A is Very Strongly more important than B	A is Strongly more important than B	A is Moderately more important than B	A is Equally Important to B	B is Moderately more important than A	B is Strongly more important than A	B is Very Strongly more important than A	B is Extremely more important than A	Parameter B
Purchasing Capacity	9	7	5	3	1	3	5	7	9	Health and Wellbeing of the people
Health and Wellbeing of the people	9	7	5	3	1	3	5	7	9	Literacy of the People
Literacy of the People	9	7	5	3	1	3	5	7	9	Purchasing Capacity

Comparison of Group of Parameters

In this section, Please indicate the relative importance of each 'group of parameters' in comparison to the other groups, given the context. The four groups are:

Social, Cultural and Environmental Conditions	<p>These are the group of parameters which arise out of the environmental, geographical, social, cultural and religious situations in the context.</p> <p>The three parameters in this group are: Environmental and Geographical Conditions; Organization of Social Networks; Religious and Cultural Beliefs of the People.</p>
Security, Legal and Political Conditions	<p>These are the group of parameters which arise out of the state of law enforcement, governance, financial security, social vulnerability, political structure and civic rights in the context.</p> <p>The three parameters in this group are: Financial Security of the People; State of Legal Enforcement; Political Practices.</p>
Access to Markets and Resources	<p>These are the group of parameters which are related to the difficulty faced by the designer or the solution provider, in accessing various forms of tangible and intangible infrastructure in the context such as manufacturing processes, Roadways, raw material, skilled labour etc.</p> <p>The five parameters in this group are: Access to Production Processes; Access to Infrastructure; Access to Raw Material; Access to Skilled Manpower; Access to Markets.</p>
Affordability, Well-being and Literacy Conditions	<p>This is the group of parameters which arise out of the inherent capability of the people to effectively engage with the solutions provided due to their health, wellbeing, literacy or affordability.</p> <p>The three parameters in this group are: Purchasing Capacity; Health and Wellbeing of the people; Literacy of the People.</p>

Consider the four group parameter above, rate the relative importance of each one in the next table.

How important is 'Parameter A' in comparison to 'Parameter B' for evaluating the success of a solution to the given problems in the context? Tick the number that best describes your opinion.										
Parameter A	A is Extremely more important than B	A is Very Strongly more important than B	A is Strongly more important than B	A is Moderately more important than B	A is Equally important to B	B is Moderately more important than A	B is Strongly more important than A	B is Very Strongly more important than A	B is Extremely more important than A	Parameter B
Social, Cultural and Environmental Conditions	9	7	5	3	1	3	5	7	9	Security, Legal and Political Conditions
Social, Cultural and Environmental Conditions	9	7	5	3	1	3	5	7	9	Access to Markets and Resources
Social, Cultural and Environmental Conditions	9	7	5	3	1	3	5	7	9	Affordability, Well-being and Literacy Conditions
Security, Legal and Political Conditions	9	7	5	3	1	3	5	7	9	Access to Markets and Resources
Security, Legal and Political Conditions	9	7	5	3	1	3	5	7	9	Affordability, Well-being and Literacy Conditions
Access to Markets and Resources	9	7	5	3	1	3	5	7	9	Affordability, Well-being and Literacy Conditions

Appendix G – TOPSIS Questionnaire

The following questionnaire was presented to experts for evaluating the various concepts using subjective parameters as part of the rough-group 'Technique for order of preference by similarity to ideal Solution' (TOPSIS) process. Details about the questionnaire can be found in Section 5.2.4.

Assessment of Design Concept <concept code number >

Based on your understanding of the context, how well do you think the concept no. <concept code number > will perform on the parameters given below? Indicate your opinion by ticking the appropriate box.

	1	2	3	4	5	6	7	8	9
Ability of the concept to fulfill its intended need.	P	V	L	M	M	M	H	V	E
Ability of the concept to be a Feasible solution	O	E	O	E	E	E	I	E	X
Ability of the concept to be a Viable solution	O	R	W	D	D	D	G	R	C
Ability of the concept to be a Desirable solution	R	Y		I	I	I	H	Y	E
Ability of the concept to be a Usable solution				U	U	U			P
Ability of the concept to be a sustainable solution		L		M	M	M		H	T
Ability of concept to <u>work within</u> existing Social, Cultural and Environmental Conditions		O						I	I
Ability of concept to <u>work within</u> existing Environmental and Geographical Conditions		W		L		H		G	O
Ability of the concept to <u>work within</u> existing Organization of Social Networks				O		I		H	N
Ability of the concept to <u>work within</u> existing Religious and Cultural Beliefs				W		G			A
Ability of concept to <u>work within</u> existing Security, Legal and Political Conditions						H			L
Ability of concept to <u>leverage</u> the existing Financial Security of the People									
Ability of concept to <u>work within</u> existing State of Legal Enforcement									

Ability of the concept to <u>leverage</u> the existing Political Practices									
<i>Ability of concept to <u>leverage</u> the existing Access to Markets and Resources</i>									
Ability of the concept to <u>leverage</u> the existing Access to Production Processes									
Ability of the concept to <u>leverage</u> the existing Access to Infrastructure									
Ability of the concept to <u>leverage</u> the existing Access to Raw Material									
Ability of the concept to <u>leverage</u> the existing Access to Skilled Manpower									
Ability of the concept to <u>leverage</u> the existing Access to Markets									
<i>Ability of concept to <u>work within</u> existing Affordability, Well-being and Literacy Conditions</i>									
Ability of the concept to <u>leverage</u> the existing Purchasing Capacity									
Ability of concept to <u>improve</u> the existing Health and Wellbeing of the people									
Ability of concept to <u>improve</u> existing Literacy of the People									

How confident are you in your assessment of this concept? (from 0= not confident to 5 = confident) = _____

-x-

Appendix H – Rough Group AHP and TOPSIS approach

The hybrid Rough-group based Multi-Criteria Decision Making (MCDM) approach used for evaluating design concepts is presented here. MCDM approaches are a set of mathematical tools used for decision making based on a set of criteria [1]. Section 5.2 discusses how the approach was used to evaluate concepts subjectively during a design conceptualisation exercise (DCE). The approach is based on a combination of the Analytical Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. The concept of Rough group sets was used for handling vagueness arising out of subjective evaluation.

Some examples of MCDM methods are Analytic hierarchy process (AHP), Analytic network process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Elimination and choice expressing reality (ELECTRE), and The Preference Ranking Organization Method for Enrichment of Evaluations (Promethee) [1]. Fuzzy set theory, Neural networks, Case-based reasoning have also been used to append MCDM theories [1].

Concept evaluation based on subjective criteria using linguistic terms is inherently vague. An evaluator may feel that a concept is 'moderately good' in a criterion, whereas another may feel it is only 'satisfactory'. Hybrid MCDM approaches have been devised to handle such vagueness in decision making [2].

Typical ways of handling vagueness in decision-making are by conducting the evaluation with multiple experts and using a fuzzy set or rough-group set to denote their overall assessment [3], [4]. These fuzzy or rough-group sets are then used with the standard MCDM approaches. Fuzzy sets are relatively difficult to implement since they use a fuzzy membership function that is subjective and is based on heuristic decisions of domain experts [4]. In contrast, a rough-group set approach overcomes this limitation by working with the original 'crisp' data set itself [1]. Moreover, the rough-group set approach considers the decision-makers risk propensity, making it less likely to influence the decision. Therefore, for our case, we selected the hybrid rough-group set based MCDM approach suggested by Song et al. [4]. The process is suitable since it considers the inherent vagueness of evaluation by experts, their propensity to risk and requires relatively less effort (considering other methods such as ANP [4]).

The following sections present the foundational information and the steps used in the selected hybrid MCDM approach.

H.1 Rough Numbers and Rough Sets

A rough number can be considered an interval with an upper and lower bound within which the 'true' number lies. These bounds are the upper and lower limits of the number. A rough number can be created from a set showing the subjective measure by several in a criterion, called the rough set [5].

The following steps for creating a rough number was adapted from Zhai et al. [6].

Assume that U is the universe containing all the objects, and there is a set of n classes of human ideas, $R = \{C_1, C_2, \dots, C_n\}$, ordered in the manner of $C_1 < C_2 < \dots < C_n$. Y is an arbitrary object of U , then the lower approximation of the C_i , upper approximation of C_i , and boundary region are defined as:

- Lower approximation : $\underline{Apr}(C_i) = U\{Y \in U/R(Y) \leq C_i\}$ (1)
- Upper approximation : $\overline{Apr}(C_i) = U\{Y \in U/R(Y) \geq C_i\}$ (2)
- Boundary region:
 $Bnd(C_i) = U\{Y \in U/R(Y) \neq C_i\} = \{Y \in U/R(Y) > C_i\} \cup \{Y \in U/R(Y) < C_i\}$
(3)

Then C_i can be represented by a rough number ($RN(C_i)$) which, is determined by its corresponding lower limit ($\underline{Lim}(C_i)$) and upper limit ($\overline{Lim}(C_i)$) where:

- Lower Limit: $\underline{Lim}(C_i) = \frac{1}{M_L} \sum R(Y) | Y \in \underline{Apr}(C_i)$ (4)
- Upper Limit: $\overline{Lim}(C_i) = \frac{1}{M_U} \sum R(Y) | Y \in \overline{Apr}(C_i)$ (5)
- Rough number: $RN(C_i) = [\underline{Lim}(C_i), \overline{Lim}(C_i)]$ (6)

Where M_L and M_U are the number of objects that contained in $\underline{Apr}(C_i)$ and $\overline{Apr}(C_i)$ respectively. The values of $\underline{Lim}(C_i)$ and $\overline{Lim}(C_i)$ are mean values of the elements in the respective sets and form an interval number and their difference can be defined as rough boundary interval ($IRBnd(C_i)$) as:

- Rough boundary Interval: $IRBnd(C_i) = \overline{Lim}(C_i) - \underline{Lim}(C_i)$ (7)

The larger the rough boundary interval, more vague the number C_i and smaller the rough boundary interval, more precise the value of C_i .

For example, if we consider a set denoting the subjective evaluation of a concept on a single criterion by 13 experts $U = \{2,5,1,6,7,1,3,5,6,2,2,7,5\}$, it has 4 classes $R = \{C_1, C_2, C_3, C_4\} = \{3, 5, 6, 7\}$. In the set R , the classes are ordered in ascending order. Now, considering equations 1, 2 and 3, a rough number denoting each of the C_1, C_2, C_3, C_4 values can be calculated. Considering one of the elements C_2 we have:

- Lower approximation : $\underline{Apr}(C_2) = \underline{Apr}(5) = \{2,5,1,1,3,5,2,2,5\}$
- Upper approximation : $\overline{Apr}(C_2) = \overline{Apr}(5) = \{5,6,7,5,6,7,5\}$
- Boundary Region: $Bnd(C_2) = Bnd(5) = \{2,1,6,7,1,3,6,2,2,7\}$
- Lower Limit: $\underline{Lim}(C_2) = \underline{Lim}(5) = \frac{1}{M_L} (2 + 5 + 1 + 1 + 3 + 5 + 2 + 2 + 5) = \frac{26}{9} = 2.89$
- Upper Limit: $\overline{Lim}(C_2) = \overline{Lim}(5) = \frac{1}{M_U} (5 + 6 + 7 + 5 + 6 + 7 + 5) = \frac{41}{7} = 5.86$
- Rough number: $RN(C_2) = [\underline{Lim}(C_2), \overline{Lim}(C_2)] = [2.89, 5.86]$
- Rough boundary Interval: $IRBnd(C_2) = \overline{Lim}(C_2) - \underline{Lim}(C_2) = 5.86 - 2.89 = 2.97$

In this example case, 2.97 can be considered as a degree of the vagueness of the element C_2 .

Because of the similarity with interval numbers, the arithmetic rules of interval numbers can also be used in a rough number. Some arithmetic rules can be summarised below:

$$\bullet \quad RN(a) \times y = [\underline{Lim}(a), \overline{Lim}(a)] \times y = [\underline{Lim}(a) \times y, \overline{Lim}(a) \times y] \quad (8)$$

$$\bullet \quad RN(a) + RN(b) = [\underline{Lim}(a), \overline{Lim}(a)] + [\underline{Lim}(b), \overline{Lim}(b)] = [\underline{Lim}(a) + \underline{Lim}(b), \overline{Lim}(a) + \overline{Lim}(b)] \quad (9)$$

$$\bullet \quad RN(a) \times RN(b) = [\underline{Lim}(a), \overline{Lim}(a)] \times [\underline{Lim}(b), \overline{Lim}(b)] = [\underline{Lim}(a) \times \underline{Lim}(b), \overline{Lim}(a) \times \overline{Lim}(b)] \quad (10)$$

Where y is a non-zero constant, and a and b are elements in the class set R .

Rough numbers created using equation six can be used in a suitably modified AHP and TOPSIS process. The following steps were adapted from the process Rough-number based hybrid AHP-TOPSIS method presented by Song et al. [4]

H.2 Analytical Hierarchy Process (AHP) and Rough AHP

In the Analytical Hierarchy Process, pairwise comparison is made between entities to understand their relative importance. The relative weights of evaluation criteria and even the concept alternatives can be selected using a pairwise comparison [7]. However, such pairwise comparison becomes difficult with too many criteria or concepts (See Section 5.2). Therefore, AHP is only used for generating criteria weights in the selected hybrid process, and TOPSIS is used for concept evaluation due to its ease of use.

The AHP process uses a standard questionnaire for pairwise comparison of alternatives. Table 5.2 shows the relative importance rating scale used in the process. Typically, the rating scale only uses odd numbers, with even numbers used only when consensus cannot be reached during evaluation [7].

Table 1: The Saaty Scale[7] used for evaluation of criterion in AHP methodology

Scale	Numerical Rating	Reciprocal Rating
Extremely more important	9	1/9
<i>Very Strongly to Extremely more important</i>	8	1/8
Very Strongly more important	7	1/7
<i>Strongly to Very Strongly more important</i>	6	1/6
Strongly more important	5	1/5
<i>Moderately to Strongly more important</i>	4	1/4
Moderately more important	3	1/3
<i>Equally to Moderately more important</i>	2	1/2
Equally Important	1	1

Overall a typical AHP process is implemented as follows:

- 1 The criteria for evaluation are first organised in a hierarchy denoting groups of criteria and their relationships.
- 2 An AHP questionnaire is used to find the relative importance of each criterion in comparison to others in the group using Sataay's Scale. The criteria groups are also similarly compared to each other. This comparison results in a decision matrix that is normalised before the next step.
- 3 A consistency ratio of the decision matrix is calculated to check if experts provided consistent answers. Eigenvectors are calculated to understand the weights for each criterion and criterion group. The weights are normalised if necessary.

In our study, a modified version of the AHP process, which uses rough sets, was employed and adapted from Song et al. [4]. Following are the steps followed for the rough-group AHP process employed in the study:

- 4 A questionnaire was used for pairwise comparison of the criteria for subjectively evaluating the concepts. The questionnaire is shown in Appendix F.
- 5 The AHP questionnaire was administered to $s = 5$ experts.
- 6 For each expert, a decision matrix was formulated for every group of pairwise comparisons (i.e. the four decision matrices for every group of CEH parameters and one matrix for the four groups), using:

$$B_e = \begin{bmatrix} 1 & x_{12}^e & \dots & x_{1m}^e \\ x_{21}^e & 1 & \dots & x_{2m}^e \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1}^e & x_{m2}^e & \dots & 1 \end{bmatrix}, \text{ where } x_{ij}^e \text{ is the relative importance given by the expert } e$$

for criterion i on criterion j , and $1 \leq i \leq m, 1 \leq j \leq m$, and $1 \leq e \leq s$, and m is the total number of criteria for this evaluation?

- 7 The Principle Eigenvalue (maximum Eigenvalue) for matrix B_e was calculated.
- 8 The Consistency Index (CI) for each matrix B_e using:

$$CI = \frac{\lambda_{max} - m}{m - 1} \quad (11)$$

Where λ_{max} is the maximum Eigenvalue calculated and m is the number of evaluated criteria [7].

- 9 The Consistency Ratio is calculated for each matrix B_e using:

$$CR = \frac{CI}{RI(m)} \quad (12)$$

Consistency ratio CR is a check that shows if the experts were consistent in their pairwise comparison of alternatives [7]. CR is a ratio between the consistency index CI and the random consistency index (RI). The random consistency index for an n dimensional matrix, $RI(n)$, is obtained from a standard Table 2 shown below [7]. The

matrix B_e will be considered consistent if the resulting ratio CR is less than 10%. If the consistency ratio is less than 10% experts are asked to review their evaluation until a consistent decision matrix is obtained.

Table 2: Random Consistency Index for matrix of 'n' dimensions

Dimension (n)	1	2	3	4	5	6	7	8	9
Random consistency index (RI).	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

- 4 A group decision matrix, \tilde{B} is built using the values of x_{ij}^e for each expert as shown:

$$\tilde{B} = \begin{bmatrix} 1 & \tilde{x}_{12} & \cdots & \tilde{x}_{1m} \\ \tilde{x}_{21} & 1 & \cdots & \tilde{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & 1 \end{bmatrix}, \text{ where } \tilde{x}_{ij} = \{x_{ij}^1, x_{ij}^2, \dots, x_{ij}^s\} \quad (14)$$

- 5 Each \tilde{x}_{ij} in matrix \tilde{B} is transformed into rough number form to obtain a rough group decision-making matrix R using the equations 1 to 6 as follows:

- a. We can get rough number form using equations 1 to 6 as:

$$RN(x_{ij}^e) = [\underline{Lim}(x_{ij}^e), \overline{Lim}(x_{ij}^e)] \text{ for each } x_{ij}^e \text{ in } \tilde{x}_{ij} \quad (15)$$

- b. We can get a rough sequence for \tilde{x}_{ij} as:

$$RN(\tilde{x}_{ij}) = \{[\underline{Lim}(x_{ij}^1), \overline{Lim}(x_{ij}^1)], [\underline{Lim}(x_{ij}^2), \overline{Lim}(x_{ij}^2)], \dots, [\underline{Lim}(x_{ij}^s), \overline{Lim}(x_{ij}^s)]\} \quad (16)$$

where s is the number of experts.

- c. Based on equations 8, 9 and 10, we can get the average rough interval, $\overline{RN}(\tilde{x}_{ij})$ as:

$$\overline{RN}(\tilde{x}_{ij}) = [\underline{Lim}(\tilde{x}_{ij}), \overline{Lim}(\tilde{x}_{ij})] \quad (17)$$

$$\underline{Lim}(\tilde{x}_{ij}) = \frac{\sum_{e=1}^s \underline{Lim}(x_{ij}^e)}{s}, \quad (18)$$

$$\overline{Lim}(\tilde{x}_{ij}) = \frac{\sum_{e=1}^s \overline{Lim}(x_{ij}^e)}{s} \quad (19)$$

Here, $\underline{Lim}(\tilde{x}_{ij})$ and $\overline{Lim}(\tilde{x}_{ij})$ are lower and upper limits of the rough number, $\overline{RN}(\tilde{x}_{ij})$

- d. Then we can get a rough group decision matrix R as follows:

$$R = \begin{bmatrix} [1,1] & [\underline{Lim}(\tilde{x}_{12}), \overline{Lim}(\tilde{x}_{12})] & \cdots & [\underline{Lim}(\tilde{x}_{1m}), \overline{Lim}(\tilde{x}_{1m})] \\ [\underline{Lim}(\tilde{x}_{21}), \overline{Lim}(\tilde{x}_{21})] & [1,1] & \cdots & [\underline{Lim}(\tilde{x}_{2m}), \overline{Lim}(\tilde{x}_{2m})] \\ \vdots & \vdots & \ddots & \vdots \\ [\underline{Lim}(\tilde{x}_{m1}), \overline{Lim}(\tilde{x}_{m1})] & [\underline{Lim}(\tilde{x}_{m2}), \overline{Lim}(\tilde{x}_{m2})] & \cdots & [1,1] \end{bmatrix} \quad (20)$$

- 6 Based on the rough group decision matrix R , we can calculate the rough weights, w_i and the normalised weights, w'_i of each criterion as follows:

$$w_i = \left[\sqrt[m]{\prod_{j=1}^m \underline{Lim}(\tilde{x}_{ij})}, \sqrt[m]{\prod_{j=1}^m \overline{Lim}(\tilde{x}_{ij})} \right] \quad (21)$$

$$w'_i = \frac{w_i}{\max(\underline{Lim}(\tilde{x}_{ij}))}, \text{ for } 1 < j < m \quad (22)$$

H.3 Rough TOPSIS

the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is a method for concept ranking. It is simple to use and can consider a non-limited number of concept alternatives in evaluation [8]. The technique can rank a set of alternatives according to their distances from an 'ideal positive and 'ideal negative solution. These ideal solutions are theoretical concepts derived from the best and worst values obtained in the evaluation.

TOPSIS has been successfully applied to solve selection/evaluation problems due to its simplicity and intuitiveness. Its also seen that the TOPSIS method can circumvent the problems of the weighted sum method[9]. Furthermore, it has been seen that TOPSIS can effectively represent the rationale of human choice [10].

The typically applied TOPSIS is a ranking process with a crisp decision matrix that considers only objective values. It also does not consider ranking by multiple decision-makers, the variation and vagueness of the evaluation by experts, or the existence of purely subjective criteria. Rough sets are thus used to make the regular TOPSIS process able to handle subjective evaluation.

Overall a typical TOPSIS process is as follows:

- 1 Each concept is evaluated on a 9 point scale (1=poor to 9=exceptional) on a set of weighted criteria. An $m \times n$ TOPSIS decision matrix is formed from the evaluation, where m is the number of concepts and n is the number of design criteria. The matrix is normalised.
- 2 The weighted normalised decision matrix is formed using criteria weights and the TOPSIS decision matrix using the Kronecker product.
- 3 The 'ideal positive' solution is found from the resulting matrix that has the highest values obtained by any concept in any criterion. Similarly, an 'ideal negative' solution is found by calculating the lowest possible values obtained by any concept in any criterion.
- 4 A separation or 'distance' between each concept and the 'ideal positive' and 'ideal negative' concept is calculated.
- 5 Concepts are then ranked based on the ratio of the distance from the 'ideal negative' solution to the sum of the distance between the 'ideal positive' and 'ideal negative' solution.

In the process described by Song et al.[4], TOPSIS is modified to use rough numbers. The rough TOPSIS methodology used in the thesis for evaluating the design concepts can be explained in the following steps:

- 6 A standard TOPSIS questionnaire [11] was used for evaluating all the concepts on a set of selected criteria by $s = 5$ experts. The TOPSIS questionnaire is shown in Appendix G and the criteria selected are explained in Section 5.2.
- 7 A concept evaluation matrix M_e is constructed as shown

$$M_e = \begin{bmatrix} z_{11}^e & z_{12}^e & \cdots & z_{1n}^e \\ z_{21}^e & z_{22}^e & \cdots & z_{2n}^e \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1}^e & z_{m2}^e & \cdots & z_{mn}^e \end{bmatrix} \quad (23)$$

where z_{ij}^e is the score given by the expert e for concept i on criterion j , and $1 \leq i \leq m$, $1 \leq j \leq n$, and $1 \leq e \leq s$, m is the number of concepts, n is the number of criteria and s is the number of experts for this evaluation.

- 8 A group concept evaluation matrix \tilde{B} is built using the values of z_{ij}^e for each expert as shown:

$$\tilde{M} = \begin{bmatrix} \tilde{z}_{11} & \tilde{z}_{12} & \cdots & \tilde{z}_{1n} \\ \tilde{z}_{21} & \tilde{z}_{22} & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{m1} & \tilde{z}_{m2} & \cdots & \tilde{z}_{mn} \end{bmatrix}, \text{ where } \tilde{z}_{ij} = \{z_{ij}^1, z_{ij}^2, \dots, z_{ij}^s\} \quad (24)$$

- 9 Each \tilde{z}_{ij} in matrix \tilde{M} is transformed into a rough number form to obtain rough group concept evaluation matrix M using the equations 1 to 6 and following a similar methodology as equations 15 to 20. This matrix will be of the following form:

$$M = \begin{bmatrix} [\underline{Lim}(\tilde{z}_{11}), \overline{Lim}(\tilde{z}_{11})] & [\underline{Lim}(\tilde{z}_{12}), \overline{Lim}(\tilde{z}_{12})] & \cdots & [\underline{Lim}(\tilde{z}_{1n}), \overline{Lim}(\tilde{z}_{1n})] \\ [\underline{Lim}(\tilde{z}_{21}), \overline{Lim}(\tilde{z}_{21})] & [\underline{Lim}(\tilde{z}_{22}), \overline{Lim}(\tilde{z}_{22})] & \cdots & [\underline{Lim}(\tilde{z}_{2n}), \overline{Lim}(\tilde{z}_{2n})] \\ \vdots & \vdots & \ddots & \vdots \\ [\underline{Lim}(\tilde{z}_{m1}), \overline{Lim}(\tilde{z}_{m1})] & [\underline{Lim}(\tilde{z}_{m2}), \overline{Lim}(\tilde{z}_{m2})] & \cdots & [\underline{Lim}(\tilde{z}_{mn}), \overline{Lim}(\tilde{z}_{mn})] \end{bmatrix} \quad (25)$$

Where, $[\underline{Lim}(\tilde{z}_{ij}), \overline{Lim}(\tilde{z}_{ij})]$ represents a rough number, and $\underline{Lim}(\tilde{z}_{ij})$ and $\overline{Lim}(\tilde{z}_{ij})$ are the lower and upper limits, respectively

- 10 We then generate the 'positive ideal solution' (PIS) and 'negative ideal solution' (NIS) values based on the characteristic of each criterion. For all benefit criteria, PIS and NIS values are the largest and the lowest values that a solution may take. Thus, the largest upper limit of all the rough numbers that a criterion takes is selected as its PIS value. Similarly, the lowest lower limit of all the rough numbers that the criterion takes is selected as its NIS value. For the Cost criterion, the largest upper limit values that a rough number interval takes are considered NIS values. The lowest lower limit of all the rough numbers that the criterion takes is selected as its PIS value. Therefore:

PIS value for criterion j :

$$p_j^+ = \{Max_i^m (\overline{Lim}(\tilde{z}_{ij})), if j \in B; Min_i^m (\underline{Lim}(\tilde{z}_{ij})), if j \in C\} \quad (26)$$

NIS value for criterion j :

$$n_j^- = \{Min_i^m (\underline{Lim}(\tilde{z}_{ij})), if j \in B; Max_i^m (\overline{Lim}(\tilde{z}_{ij})), if j \in C\} \quad (27)$$

Here B and C are the benefit and cost criteria, respectively. In our case, all evaluation criteria were benefit criteria.

- 11 Next, the deviation coefficient for each rough number $[\underline{Lim}(\tilde{z}_{ij}), \overline{Lim}(\tilde{z}_{ij})]$ is calculated. The deviation coefficient depicts the distance between the rough number and its PIS and NIS values and is itself a rough number. The deviation coefficient is calculated using the distance between the rough number and its PIS and NIS values. Thus

The deviation coefficient of the rough number from the PIS values can be calculated using the equations:

$$d_{ij}^{+L} = p_j^+ - \overline{Lim}(\tilde{z}_{ij}), if j \in B \quad (28)$$

$$d_{ij}^{+U} = p_j^+ - \underline{Lim}(\tilde{z}_{ij}), if j \in B \quad (29)$$

Here, the rough number that denotes the distance of the rough number and the PIS solution is $[d_{ij}^{+L}, d_{ij}^{+U}]$, where d_{ij}^{+L} and d_{ij}^{+U} represent the lower and the upper limits of the distance coefficient rough number.

The deviation coefficient of the rough number from the NIS can be shown using the equations:

$$d_{ij}^{-L} = \underline{Lim}(\tilde{z}_{ij}) - n_j^-, if j \in B \quad (30)$$

$$d_{ij}^{-U} = \overline{Lim}(\tilde{z}_{ij}) - n_j^-, if j \in B \quad (31)$$

Here, the rough number that denotes the distance of the rough number and the NIS solution is $[d_{ij}^{-L}, d_{ij}^{-U}]$, where d_{ij}^{-L} and d_{ij}^{-U} represent the lower and the upper limits of the distance coefficient rough number.

- 12 The deviation coefficient matrix D^+ and D^- are then established using the deviation coefficients calculated in step 4 as follows:

$$D^- = \begin{bmatrix} [d_{11}^{-L}, d_{11}^{-U}] & [d_{12}^{-L}, d_{12}^{-U}] & \dots & [d_{1n}^{-L}, d_{1n}^{-U}] \\ [d_{21}^{-L}, d_{21}^{-U}] & [d_{22}^{-L}, d_{22}^{-U}] & \dots & [d_{2n}^{-L}, d_{2n}^{-U}] \\ \vdots & \vdots & \ddots & \vdots \\ [d_{m1}^{-L}, d_{m1}^{-U}] & [d_{m3}^{-L}, d_{m3}^{-U}] & \dots & [d_{mn}^{-L}, d_{mn}^{-U}] \end{bmatrix} \quad (32)$$

$$D^+ = \begin{bmatrix} [d_{11}^{+L}, d_{11}^{+U}] & [d_{12}^{+L}, d_{12}^{+U}] & \dots & [d_{1n}^{+L}, d_{1n}^{+U}] \\ [d_{21}^{+L}, d_{21}^{+U}] & [d_{22}^{+L}, d_{22}^{+U}] & \dots & [d_{2n}^{+L}, d_{2n}^{+U}] \\ \vdots & \vdots & \ddots & \vdots \\ [d_{m1}^{+L}, d_{m1}^{+U}] & [d_{m3}^{+L}, d_{m3}^{+U}] & \dots & [d_{mn}^{+L}, d_{mn}^{+U}] \end{bmatrix} \quad (33)$$

- 13 We then normalise the deviation coefficient matrix D^+ and D^- for each criterion. This is done by dividing the lower and upper bounds in each rough number by the maximum value of the deviation coefficient in that row as follows:

$$d_{ij}^{\prime+L} = \frac{d_{ij}^{+L}}{\text{Max}_{i=1}^m \{\text{Max}[d_{ij}^{+L}, d_{ij}^{+U}]\}}, \quad d_{ij}^{\prime+U} = \frac{d_{ij}^{+U}}{\text{Max}_{i=1}^m \{\text{Max}[d_{ij}^{+L}, d_{ij}^{+U}]\}} \quad (34)$$

$$d_{ij}^{\prime-L} = \frac{d_{ij}^{-L}}{\text{Max}_{i=1}^m \{\text{Max}[d_{ij}^{-L}, d_{ij}^{-U}]\}}, \quad d_{ij}^{\prime-U} = \frac{d_{ij}^{-U}}{\text{Max}_{i=1}^m \{\text{Max}[d_{ij}^{-L}, d_{ij}^{-U}]\}} \quad (35)$$

Where, $d_{ij}^{\prime+L}$ and $d_{ij}^{\prime+U}$ represent the lower and upper limits of normalised deviation coefficients between a rough number and PIS. $d_{ij}^{\prime-L}$ and $d_{ij}^{\prime-U}$ Represent the lower and upper limits of normalised deviation coefficients between a rough number and NIS.

- 14 The normalised decision coefficient matrixes D'^- and D'^+ are then calculated as follows:

$$D'^- = \begin{bmatrix} [d_{11}^{\prime-L}, d_{11}^{\prime-U}] & [d_{12}^{\prime-L}, d_{12}^{\prime-U}] & \dots & [d_{1n}^{\prime-L}, d_{1n}^{\prime-U}] \\ [d_{21}^{\prime-L}, d_{21}^{\prime-U}] & [d_{22}^{\prime-L}, d_{22}^{\prime-U}] & \dots & [d_{2n}^{\prime-L}, d_{2n}^{\prime-U}] \\ \vdots & \vdots & \ddots & \vdots \\ [d_{m1}^{\prime-L}, d_{m1}^{\prime-U}] & [d_{m2}^{\prime-L}, d_{m2}^{\prime-U}] & \dots & [d_{mn}^{\prime-L}, d_{mn}^{\prime-U}] \end{bmatrix} \quad (36)$$

$$D'^+ = \begin{bmatrix} [d_{11}^{\prime+L}, d_{11}^{\prime+U}] & [d_{12}^{\prime+L}, d_{12}^{\prime+U}] & \dots & [d_{1n}^{\prime+L}, d_{1n}^{\prime+U}] \\ [d_{21}^{\prime+L}, d_{21}^{\prime+U}] & [d_{22}^{\prime+L}, d_{22}^{\prime+U}] & \dots & [d_{2n}^{\prime+L}, d_{2n}^{\prime+U}] \\ \vdots & \vdots & \ddots & \vdots \\ [d_{m1}^{\prime+L}, d_{m1}^{\prime+U}] & [d_{m2}^{\prime+L}, d_{m2}^{\prime+U}] & \dots & [d_{mn}^{\prime+L}, d_{mn}^{\prime+U}] \end{bmatrix} \quad (37)$$

- 15 Based on the normalised decision coefficient matrixes D'^- and D'^+ , we can calculate the separation measure or the 'weighted normalised deviation' of each concept alternative. The separation measures are numbers that indicate the difference between the concept alternative and the PIS and NIS values. These can also be represented in the form of rough numbers. The separation measure is calculated as follows:

$$S_i^+ = [S_i^{+L}, S_i^{+U}] = \sum_{j=1}^n [w_j' \times d_{ij}^{\prime+}] \quad (38)$$

$$S_i^- = [S_i^{-L}, S_i^{-U}] = \sum_{j=1}^n [w_j' \times d_{ij}^{\prime-}] \quad (39)$$

Where Separation measures S_i^+ and S_i^- Represent the weighted normalised deviation of alternative i from its PIS and NIS values, respectively. w_j' is the rough number weight of the j th criterion obtained from the rough AHP method in equation 22, and $d_{ij}^{\prime-}$ and $d_{ij}^{\prime+}$ are the normalised rough number deviation coefficient for each alternative, $[d_{ij}^{\prime-L}, d_{ij}^{\prime-U}]$ and $[d_{ij}^{\prime+L}, d_{ij}^{\prime+U}]$ Respectively.

- 16 For judging the sensitivity of the analysis, Song et al. [4] propose the 'optimistic indicator' α ($0 \leq \alpha \leq 1$) to transform the separation measures S_i^+ and S_i^- into crisp values. If decision-makers are more optimistic, we can consider α to take a bigger value ($\alpha > 0.5$)

and, if decision-makers are more pessimistic, it can take a smaller value for α ($\alpha < 0.5$). If decision-makers keep a realistic and moderate attitude, in other words, neither very optimistic nor very pessimistic, α is considered to have a value of 0.5. The separation measures are converted into crisp values using the following equations:

$$S_i^{+*} = (1 - \alpha)S_i^{+L} + \alpha S_i^{+U} \quad (40)$$

$$S_i^{-*} = (\alpha)S_i^{-L} + (1 - \alpha)S_i^{-U} \quad (41)$$

S_i^{+*} and S_i^{-*} represent the crisp value of the rough number S_i^+ and S_i^- , respectively.

In the TOPSIS questionnaire, experts were asked how confident they were in evaluating the concept, which they answered on a scale of 0 to 5 (0=not confident at all, 5 = very confident). The average of this answer was obtained for calculating the α value. The α value selected is the discrete value in a linearly spaced array with six elements from 1 to 9, which is greater than the calculated average of the answer.

In other words, we selected the α value from the linear array [0.1, 0.26, 0.42, 0.58, 0.74, 0.9], which was closest to the average of the score given by all experts for a concept. The linear array is an even distribution of numbers starting from 0.1 to 0.9. For a concept where the experts were, on average, not confident at all with their evaluation, the value chosen will be 0.1, and if they were very confident, the value of 0.9 would be selected. The assumption is that experts are at least 10 % confident of their evaluations when they are not confident at all and at most 90% confident if they were very confident with their evaluations.

- 17 Finally, the Closeness Coefficients (CC_i) of all alternatives can be calculated and the concepts can be ranked based on the value. A concept alternative with a larger value of CC_i is a better concept in terms of the subjective evaluation done by experts in the given parameters since it is closer to the PIS and farther away from the NIS.

$$CC_i = \frac{S_i^{-*}}{S_i^{-*} + S_i^{+*}} \quad (42)$$

In addition to the above steps, we also calculate the CC_i values for the different alpha values, $\alpha = \{0.1, 0.26, 0.42, 0.58, 0.74, 0.9\}$. These α values help us understand the effect of expert confidence on the evaluation and understand rank reversal effects [9].

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Appendix I – MATLAB® Script for Rough AHP and TOPSIS

The script used for executing the rough group AHP and TOPS process shown in Appendix H is provided here for review. The outcomes of the script is an array of CC_i values for each concept.

The following script is for calculating the Consistency ratio for AHP evaluation (Step 5 and 6 Appendix H)

```
clear;
load ('\AllAHPCalculationOutputs.mat') %AHP data is loaded
RI = [0,0,0.58,0.9,1.12,1.24,1.32,1.41,1.45];
ConsistencyRatioForExpert = zeros(5);

for i=1:5
    for j = 1:5
        TestMatrix = AllExpertsAHPdata{i,j}; % get values form matrix with AHP data
        [r,c] = size(TestMatrix);
        RI(r);
        consistencyIndex12 = (eigs(TestMatrix,1)-r)/(r-1);
        consistencyRatioPercent13 = 100*(consistencyIndex12/RI(r));

        ConsistencyRatioForExpert (i,j) = consistencyRatioPercent13;

        if(consistencyRatioPercent13<10)
            'Consistant'
        else
            'INconsistent'
        end
    end
end
end
```

The following function returns a cell with the RoughNumber cell containing a rough lower limit and rough upper limit of each element in the input array.

E.g Input array = [3,5,1,4,5] Outputcell = {[2,4.25],[3.60,5],[1,3.6] ,[2.66,4.66],[3.60,5]}

```
function outputCell = roughNumber(inputArray)
upperLimArray = [];
lowerLimArray = [];

if isvector(inputArray) && not (ischar(inputArray))
    InputSize = size(inputArray, 2); % find no of columns
    outputCell = cell(1,InputSize);
    if InputSize >0 % compute only when input array is non zero size
        uniqueClasses = unique(inputArray);
        NoOfClasses = size(uniqueClasses, 2);
        uniqueRoughElement = cell(1,NoOfClasses);
        %</Compute the rough no range for each unique element
```

```

for u=1:NoOfClasses
    for i=1:InputSize
        if inputArray(1,i)>= uniqueClasses(u)
            if isempty(upperLimArray)
                upperLimArray = inputArray(1,i);
            else
                upperLimArray = [upperLimArray, inputArray(1,i)];
            end
        end

        if inputArray(1,i)<= uniqueClasses(u)
            if isempty(lowerLimArray)
                lowerLimArray = inputArray(1,i);
            else
                lowerLimArray = [lowerLimArray, inputArray(1,i)];
            end
        end
    end

    uniqueRoughElement{u} = [mean(lowerLimArray),mean(upperLimArray)];
    lowerLimArray = [];
    upperLimArray = [];
end
%End computation for rough no range for each unique element/>
%</Assign the rough number into the output cell

for u=1:NoOfClasses
    for i=1:InputSize
        if inputArray(1,i)== uniqueClasses(u)
            outputCell{i} = uniqueRoughElement{u};
        end
    end
end

%End Assignment of rough into output cell/>
end
else
    outputCell = {};
end
%function end
end

```

The following script is for implementing the rough-group AHP steps shown in Appendix H.

```

clear; %clear all existing Variables
%get all data from the excel file to a cell array AllAHPData{}.
addpath ('\MatlabScripts'); % Rough Number Function is here
folderPath = '<<<FILE PATH GOES HERE>>>';
fileName = 'AHPDataAllExperts.xlsx'; % File name storing the data
AHPfileLocation = fullfile(folderPath,fileName);
expert = 5; % number of experts
SheetsInExcel = cell(1,5); % initialising a cell array to store the name of the
sheets in excel file
SheetsInExcel = {'Bv', 'Di', 'Pr', 'Sh', 'So'}; %sheet names in excel file. access
this as SheetsInExcel{n}, where n is the expert number
AllExpertsAHPdata = cell(expert,5); % for storing the AHP data AllAHPdata{2,4} is the
4th decision matrix for the 2nd expert

```

```

for n = 1:expnt %expnt is the expert no
    for decMat = 1:5 % decMat is the decision matrix number
        if decMat == 1
            % copy the 1st decMat of expnt into the cell location to
AllExpertsAHPdata{expnt,1}
            AllExpertsAHPdata{n,decMat} =
table2array(readtable(AHPfileLocation,"Sheet",SheetsInExcel{n},
"Range","B2:D4","ReadVariableNames",false));
            elseif decMat == 2
            AllExpertsAHPdata{n,decMat} =
table2array(readtable(AHPfileLocation,"Sheet",SheetsInExcel{n},
"Range","B6:D8","ReadVariableNames",false));
            elseif decMat == 3
            AllExpertsAHPdata{n,decMat} =
table2array(readtable(AHPfileLocation,"Sheet",SheetsInExcel{n},
"Range","B10:F14","ReadVariableNames",false));
            elseif decMat == 4
            AllExpertsAHPdata{n,decMat} =
table2array(readtable(AHPfileLocation,"Sheet",SheetsInExcel{n},
"Range","B16:D18","ReadVariableNames",false));
            elseif decMat == 5
            AllExpertsAHPdata{n,decMat} =
table2array(readtable(AHPfileLocation,"Sheet",SheetsInExcel{n},
"Range","B20:E23","ReadVariableNames",false));
            else
                %Error Break program
                'Error i going to 6'
                break;
            end
        end
    end
end

SingleExpntDecisionMatrix = AllExpertsAHPdata {1,1};
GroupDecisionMatx = cell(1,5); % this will be a single matrix of decisions of all
experts. A matrix of matrices
% initialize the GroupDecisionMatrix
for decMat=1:5
    if decMat == 3
        GroupDecisionMatx{1,decMat} = cell(5);
    elseif decMat == 5
        GroupDecisionMatx{1,decMat} = cell(4);
    else
        GroupDecisionMatx{1,decMat} = cell(3);
    end
end

%combine the decision matrices into one and build equation 14.
decMat = 5; %there are 5 decsison matrixes
for n = 1:expnt
    for c=1:decMat
        SingleExpntDecisionMatrix = AllExpertsAHPdata {n,c};
        [row,col] = size(SingleExpntDecisionMatrix);
        for i=1:row
            for j=1:col
                if i==j
                    GroupDecisionMatx{1,c}{i,j} = 1;
                else

```

```

                GroupDecisionMatx{1,c}{i,j} = [GroupDecisionMatx{1,c}{i,j},
SingleExprtDecisionMatrix(i,j)];
            end
        end
    end
end

%develop the Rough number Group Decision matrix
roughNoGrpDecMat = cell(1,5); %5= no of criteria matx
for c=1:5
    %cycle through 5 decision matrixes and transform each into a rough
    %number form
    [row, col] = size(GroupDecisionMatx{1,c});
    tempcell = cell(row, col);
    for i=1:row
        for j =1:col
            tempcell{i,j} = roughNumber(GroupDecisionMatx{1,c}{i,j});
        end
    end
    roughNoGrpDecMat{1,c}=tempcell;
    tempcell = {};
end

singRoughNoGDM = cell(1,5);
avgLowRN = 0;
avgUpRN = 0;
for c=1:5
    [row, col]= size(roughNoGrpDecMat{1,c});
    tempcell = cell(row, col);
    for i=1:row
        for j=1:col
            [inrow, incol] = size(roughNoGrpDecMat{1,c}{i,j});
            for y=1:incol
                avgLowRN = avgLowRN + roughNoGrpDecMat{1,c}{i,j}{1,y}(1);
                avgUpRN = avgUpRN + roughNoGrpDecMat{1,c}{i,j}{1,y}(2);
            end
            avgLowRN = avgLowRN/incol;
            avgUpRN = avgUpRN/incol;
            tempcell{i,j} = [avgLowRN, avgUpRN];
            avgLowRN = 0;
            avgUpRN = 0;
        end
    end
    singRoughNoGDM{1,c} = tempcell;
    tempcell = {};
end

%step 8 over singRoughNoGDM is the rough no Decision matirx R. has 5 cells
%for each of the cell is a matrix.

% step 9 onwards
weightcell = cell(1,5);
WeightDashCell = cell(1,5);
tempArray = [];
geoAvgLowRN = 1;
geoAvgUpRN = 1;
maxUpLim = 0;

```

```

for c=1:5 % cycel through the criteria matrixes
    [row, col] = size(singRoughNoGDM{1,c});
    tempcell = cell(row,1);
    tempcell2 = cell(row,1);
    for i=1:row
        for j=1:col
            geoAvgLowRN = geoAvgLowRN * singRoughNoGDM{1,c}{i,j}(1);
            geoAvgUpRN = geoAvgUpRN * singRoughNoGDM{1,c}{i,j}(2);
            tempArray = [tempArray, singRoughNoGDM{1,c}{i,j}(2)];
        end
        geoAvgLowRN = nthroot(geoAvgLowRN, col);
        geoAvgUpRN = nthroot(geoAvgUpRN, col);
        maxUpLim = max(tempArray);
        tempcell{i,1} = [geoAvgLowRN,geoAvgUpRN];
        tempcell2{i,1} = tempcell{i,1}./maxUpLim; %normalization method based on Zhu
et.al 2015. Song, Ming and Wu 2013 doesn't have normalization
        geoAvgLowRN = 1;
        geoAvgUpRN = 1;
        maxUpLim = 0;
        tempArray = [];
    end
    weightcell{1,c}=tempcell;
    WeightDashCell{1,c} = tempcell2; %normalized weights as per Zhu et.al 2015
    tempcell = {};
    tempcell2= {};
end

%Following Section is to make a single column of all the weights and
% normalised weights. Each sub-weight Rough Number is multiplied with the Parent
weight from the hierarchy like  $RN1 \times RN2 = (L1, U1) \times (L2, U2) = (L1 \times L2, U1 \times U2)$ 
% the outputs are saved in the normalised weights file

CriteriaWeightsSingleCol= cell(18,1); %for storing all the weights in order
CriteriaWeightsNormalSingleCol = cell(18,1);

MultipliedWeightsCell = cell(1,5);
MultiplieNormalWeightCell = cell(1,5);

for c= 1:4
    v=c;
    tc =c;
    if v>1
        while v>1
            tc = tc+size(weightcell{v-1},1);
            v=v-1;
        end
    end

    CriteriaWeightsSingleCol{tc} = weightcell{5}{c};
    CriteriaWeightsNormalSingleCol{tc} = WeightDashCell{5}{c};

    row = size(weightcell{c},1)

    for i=1:row
        CriteriaWeightsSingleCol{tc+i} = [weightcell{c}{i}(1)*weightcell{5}{c}(1),
weightcell{c}{i}(2)*weightcell{5}{c}(2)];
    end
end

```

```

CriteriaWeightsNormalSingleCol{tc+i} =
[WeightDashCell{c}{i}(1)*WeightDashCell{5}{c}(1),
WeightDashCell{c}{i}(2)*WeightDashCell{5}{c}(2)];

MultipliedWeightsCell{1,c}{i,1} = [weightcell{c}{i}(1)*weightcell{5}{c}(1),
weightcell{c}{i}(2)*weightcell{5}{c}(2)];
MultiplieNormalWeightCell{1,c}{i,1} =
[WeightDashCell{c}{i}(1)*WeightDashCell{5}{c}(1),
WeightDashCell{c}{i}(2)*WeightDashCell{5}{c}(2)];

end
end

MultipliedWeightsCell{5} = weightcell{5}
MultiplieNormalWeightCell{5} = WeightDashCell {5}

clear("tc", "c", "v", "y", "tempcell", "tempcell2", "tempArray", "row", "n",
"maxUpLim", "j", "i", "incol", "inrow", "geoAvgLowRN", "geoAvgUpRN", "expnt",
"decMat", "avgLowRN", "avgLowRN", "AHPfileLocation", "c", "avgUpRN", "col")
save(fullfile(folderPath, 'NormalizedWeights.mat'), "weightcell", "WeightDashCell",
"CriteriaWeightsSingleCol", "CriteriaWeightsNormalSingleCol",
"MultipliedWeightsCell", "MultiplieNormalWeightCell");
save(fullfile(folderPath, 'AllAHPCalculationOutputs.mat'));

```

The following script implements the rough TOPSIS approach till the creation of normalised deviation coefficient matrices (i.e. till equation 37 in Appendix H)

```

clear;
folderPath = <<<FILE PATH GOES HERE>>>;
fileName = 'TOPSISDataAllExperts.xlsx'; %filename storing all TOPSIS data
TOPSISfileLocation = fullfile(folderPath,fileName);
SheetsInExcel = {'Bh', 'Di', 'Pr', 'Sh', 'So'}; %sheet names in excel file. access
this as SheetsInExcel{n}, where n is the expert number
TopsisRange = 'C8:AW25'; %Location of the Concept evaluations
NonTopsisRange = 'C2:AW7'; % other non TOPSIS criteria
ConfidenceRange = 'C26:AW26'; %for confidence data

nExp = 5; % number of experts 5
nCri = 18; % number of CEH Criteria. (variables named with TOPSIS)
nFDVU = 6; % number of FVDUS Criteria. (Variables named with nonTOPSIS)
AllTopsisDataCell = cell(1,nExp); % cell for all CEH criteria data
NonTopsisDataCell = cell(1,nExp); % cell for FVDUS criteria data
ExpertConfidenceData = cell(1,nExp); % cell for recording confidence data

% read the dataset into the cell variables
for e = 1:nExp
AllTopsisDataCell{1,e} =
table2array(readtable(TOPSISfileLocation, "Sheet", SheetsInExcel{e},
"Range", TopsisRange, "ReadVariableNames", false));
NonTopsisDataCell{1,e} =
table2array(readtable(TOPSISfileLocation, "Sheet", SheetsInExcel{e},
"Range", NonTopsisRange, "ReadVariableNames", false));

```

```

ExpertConfidenceData{1,e} =
table2array(readtable(TOPSISfileLocation,"Sheet",SheetsInExcel{e},
"Range",ConfidenceRange,"ReadVariableNames",false));

%transpose the data matrixes so that the rows are the concepts and the
%columns are the criteria for following the calculations

AllTopsisDataCell{1,e} = transpose(AllTopsisDataCell{1,e});
NonTopsisDataCell{1,e} = transpose(NonTopsisDataCell{1,e});
ExpertConfidenceData{1,e} = transpose(ExpertConfidenceData{1,e});

end

%number of concepts in the file is nCnpt
[nCnpt, col] = size(AllTopsisDataCell{1,1});
clearvars("col");
% combine the data to form the collated matrix step 2 (eq 24)
combTopsisCell = cell(nCnpt,nCri); % initialize the combined decision cell
combNONTopsisCell = cell(nCnpt,nFDVU);

for i=1:nCnpt
    for j=1:nCri
        tempArray = zeros(1,nExp);
        for e=1:nExp
            tempArray(1,e) = AllTopsisDataCell{1,e}(i,j);
        end
        combTopsisCell{i,j} = tempArray;
    end

    for j=1:nFDVU
        tempArray = zeros(1,nExp);
        for e=1:nExp
            tempArray(1,e) = NonTopsisDataCell{1,e}(i,j);
        end
        combNONTopsisCell{i,j} = tempArray;
    end
end

% start making Rough number combined cell step 3 eq 30

combRNArrTopsisCell = cell(nCnpt, nCri);
RNTopsisEvalCell = cell(nCnpt, nCri);

combRNArrNONTopsisCell = cell(nCnpt, nFDVU);
RNNONTopsisEvalCell = cell(nCnpt, nFDVU);

for i=1:nCnpt
    for j=1:nCri
        combRNArrTopsisCell{i,j} = roughNumber(combTopsisCell{i,j});
        RNLow = 0;
        RNUp = 0;
        for e=1:nExp
            RNLow = RNLow + combRNArrTopsisCell{i,j}{1,e}(1);
            RNUp = RNUp + combRNArrTopsisCell{i,j}{1,e}(2);
        end
        %         RNLow
        %         RNUp
    end
    %     RNLow
    %     RNUp
end

```

```

        RNLow = RNLow/nExp;
        RNUp = RNUp/nExp;
        RNTopsisEvalCell{i,j} = [RNLow,RNUp]; % output of eq. 30
    end

    for j=1:nFDVU
        combRNArrNONTopsisCell{i,j} = roughNumber(combNONTopsisCell{i,j});
        RNLow = 0;
        RNUp = 0;
        for e=1:nExp
            RNLow = RNLow + combRNArrNONTopsisCell{i,j}{1,e}(1);
            RNUp = RNUp + combRNArrNONTopsisCell{i,j}{1,e}(2);
        %         RNLow
        %         RNUp
        end
        %         RNLow
        %         RNUp
        RNLow = RNLow/nExp;
        RNUp = RNUp/nExp;
        RNNONTopsisEvalCell{i,j} = [RNLow,RNUp]; % output of eq. 30
    end
end

%completed Step 3 and Obtained output for Eq 30 in RNTopsisEvalCell
%Start Step 5, to obtain the PIS and NIS from the data. PIS and NIS are
%crisp vectors

positiveIdealSol = zeros(1,nCri); %vector with 18 columns one for each criteria
negativeIdealSol = zeros(1,nCri);

for j=1:nCri
    tempArray = zeros(nCnpt,1);
    tempArrayUp = zeros(nCnpt,1);
    for i=1:nCnpt
        tempArray(i,1) = RNTopsisEvalCell{i,j}(1);
        tempArrayUp(i,1) = RNTopsisEvalCell{i,j}(2);
    end
    negativeIdealSol(1,j) = min(tempArray);
    positiveIdealSol(1,j) = max(tempArrayUp);
end
clearvars("tempArray","tempArrayUp"); % clear temp variables

positiveIdealSolNONTopsis = zeros(1,nFDVU); %vector with 18 columns one for each
criteria
negativeIdealSolNONTopsis = zeros(1,nFDVU);

for j=1:nFDVU
    tempArray = zeros(nCnpt,1);
    tempArrayUp = zeros(nCnpt,1);
    for i=1:nCnpt
        tempArray(i,1) = RNNONTopsisEvalCell{i,j}(1);
        tempArrayUp(i,1) = RNNONTopsisEvalCell{i,j}(2);
    end
    negativeIdealSolNONTopsis(1,j) = min(tempArray);
    positiveIdealSolNONTopsis(1,j) = max(tempArrayUp);
end
clearvars("tempArray","tempArrayUp"); % clear temp variables

% Step 6 and 7 creation of rough no Deviation cell

```

```

PISCnptDeviationCell = cell(nCnpt,nCri);
NISCnptDeviationCell = cell(nCnpt,nCri);
for i=1:nCnpt
    for j=1:nCri
        PISCnptDeviationCell{i,j} = [positiveIdealSol(1,j)-RNTopsisEvalCell{i,j}(2),
positiveIdealSol(1,j)-RNTopsisEvalCell{i,j}(1)]; % All are benefit criteria
        NISCnptDeviationCell{i,j} = [RNTopsisEvalCell{i,j}(1)-negativeIdealSol(1,j),
RNTopsisEvalCell{i,j}(2)-negativeIdealSol(1,j)]; % All are benefit criteria
    end
end

NONTopsisPISCnptDeviationCell = cell(nCnpt,nFDVU);
NONTopsisNISCnptDeviationCell = cell(nCnpt,nFDVU);
for i=1:nCnpt
    for j=1:nFDVU
        NONTopsisPISCnptDeviationCell{i,j} = [positiveIdealSolNONTopsis(1,j)-
RNNONTopsisEvalCell{i,j}(2), positiveIdealSolNONTopsis(1,j)-
RNNONTopsisEvalCell{i,j}(1)]; % All are benefit criteria
        NONTopsisNISCnptDeviationCell{i,j} = [RNNONTopsisEvalCell{i,j}(1)-
negativeIdealSolNONTopsis(1,j), RNNONTopsisEvalCell{i,j}(2)-
negativeIdealSolNONTopsis(1,j)]; % All are benefit criteria
    end
end

%Step 8 making the normalized Deviation matrices
NormPISDevnCell = cell(nCnpt, nCri);
NormNISDevnCell = cell(nCnpt, nCri);

for j=1:nCri
    maxRowDevPIS = max([PISCnptDeviationCell{:,j}]);
    maxRowDevNIS = max([NISCnptDeviationCell{:,j}]);
    for i=1:nCnpt
        NormPISDevnCell{i,j} = PISCnptDeviationCell{i,j}./maxRowDevPIS;
        NormNISDevnCell{i,j} = NISCnptDeviationCell{i,j}./maxRowDevNIS;
    end
end

NONTopsisNormPISDevnCell = cell(nCnpt, nFDVU);
NONTopsisNormNISDevnCell = cell(nCnpt, nFDVU);

for j=1:nFDVU
    maxRowDevPIS = max([NONTopsisPISCnptDeviationCell{:,j}]);
    maxRowDevNIS = max([NONTopsisNISCnptDeviationCell{:,j}]);
    for i=1:nCnpt
        NONTopsisNormPISDevnCell{i,j} =
NONTopsisPISCnptDeviationCell{i,j}./maxRowDevPIS;
        NONTopsisNormNISDevnCell{i,j} =
NONTopsisNISCnptDeviationCell{i,j}./maxRowDevNIS;
    end
end

% Cleanup

clearvars("RNTopsisEvalCell", "PISCnptDeviationCell", "NISCnptDeviationCell",
"maxRowDevNIS", "maxRowDevPIS", "combTopsisCell", "combRNArrTopsisCell")
clearvars("RNNONTopsisEvalCell", "NONTopsisPISCnptDeviationCell",
"NONTopsisNISCnptDeviationCell", "combNONTopsisCell", "combRNArrNONTopsisCell")
clearvars("TopsisRange", "TOPSISfileLocation", "NonTopsisRange", "ConfidenceRange")

```

```
clearvars("i", "j", "e", "RNUp", "RNLow")

save('RoughTOPSISOutput.mat')
% form here on for calculating the weighted Closeness coefficients move to
% ClosenessCoefficientsCalculation.mlx
```

The following script was used for rough TOPSIS calculations post step 10 (Appendix H). Additionally, Closeness coefficient values are also calculated with multiple alpha values, as mentioned in Step 12 (Appendix H)

```
%start the work from step 9 onwards to calculate the closeness coefficients

clear; %clear all existing Variables
folderPath = '<<<FILE PATH GOES HERE>>>';
load(fullfile(folderPath, 'AllAHPCalculationOutputs.mat'));
load(fullfile(folderPath, 'RoughTOPSISOutput.mat'));

PosFullSeparationCell = cell(nCnpt, nCri);
NegFullSeparationCell = cell(nCnpt, nCri);

for i=1:nCnpt
    for j=1:nCri

PosFullSeparationCell{i,j}=[NormPISDevnCell{i,j}(1)*CriteriaWeightsNormalSingleCol{j}
(1), NormPISDevnCell{i,j}(2)*CriteriaWeightsNormalSingleCol{j}(2)];

NegFullSeparationCell{i,j}=[NormNISDevnCell{i,j}(1)*CriteriaWeightsNormalSingleCol{j}
(1), NormNISDevnCell{i,j}(2)*CriteriaWeightsNormalSingleCol{j}(2)];
        end
    end

PosSeparation = cell(nCnpt,1);
NegSeparation = cell(nCnpt,1);

for i=1:nCnpt
    tempVar = [PosFullSeparationCell{i,:}];
    tempVar = tempVar(1,1:2:end);
    tempLowLim =
sum(tempVar(1,2:4))+sum(tempVar(1,6:8))+sum(tempVar(1,10:14))+sum(tempVar(1,16:18));

    tempVar = [PosFullSeparationCell{i,:}];
    tempVar = tempVar(1,2:2:end);
    tempUpLim =
sum(tempVar(1,2:4))+sum(tempVar(1,6:8))+sum(tempVar(1,10:14))+sum(tempVar(1,16:18));

    PosSeparation{i,1} = [tempLowLim, tempUpLim]; % this is S+i
    tempLowLim = 0;
    tempUpLim = 0;
    tempVar = [NegFullSeparationCell{i,:}];
    tempVar = tempVar(1,1:2:end);
    tempLowLim =
sum(tempVar(1,2:4))+sum(tempVar(1,6:8))+sum(tempVar(1,10:14))+sum(tempVar(1,16:18));

    tempVar = [NegFullSeparationCell{i,:}];
    tempVar = tempVar(1,2:2:end);
```

```

    tempUpLim =
sum(tempVar(1,2:4))+sum(tempVar(1,6:8))+sum(tempVar(1,10:14))+sum(tempVar(1,16:18));

    NegSeperation{i,1} = [tempLowLim, tempUpLim]; %this is S-i
end

clearvars("tempVar", "tempLowLim", "tempUpLim");

NONTOPSISPosSeparation = cell(nCnpt,1);
NONTOPSISNegSeparation = cell(nCnpt,1);

for i=1:nCnpt
    tempVar = [NONTopsisNormPISDevnCell{i,:}];
    tempVar = tempVar(1,1:2:end);
    tempLowLim = sum(tempVar); % weights of the FVDUS criteria is considered 1 i.e.
all are equally weighted.
    tempVar = [NONTopsisNormPISDevnCell{i,:}];
    tempVar = tempVar(1,2:2:end);
    tempUpLim = sum(tempVar);

    NONTOPSISPosSeparation{i,1} = [tempLowLim, tempUpLim];

    tempVar = [NONTopsisNormNISDevnCell{i,:}];
    tempVar = tempVar(1,1:2:end);
    tempLowLim = sum(tempVar);

    tempVar = [NONTopsisNormNISDevnCell{i,:}];
    tempVar = tempVar(1,2:2:end);
    tempUpLim = sum(tempVar);

    NONTOPSISNegSeparation{i,1} = [tempLowLim, tempUpLim];
end

alphaVal = linspace(0.1,0.9,6) % a linerly spaced array for the confidence intervals
%0.1000  0.2600  0.4200  0.5800  0.7400  0.9000
%here we calculate the closeness coefficients based on these alpha values

PosCrispSeparationWALLAlpha = zeros(nCnpt,length(alphaVal));
NegCrispSeparationWALLAlpha = zeros(nCnpt,length(alphaVal));

for i=1:nCnpt
    for j=1:length(alphaVal)
        PosCrispSeparationWALLAlpha(i,j) = (1-alphaVal(j))*PosSeparation{i}(1) +
alphaVal(j)*PosSeparation{i}(2);
        NegCrispSeparationWALLAlpha(i,j) = alphaVal(j)*NegSeparation{i}(1) + (1-
alphaVal(j))*NegSeparation{i}(2);
    end
end

NONTopsisPosCrispSeparationWALLAlpha = zeros(nCnpt,length(alphaVal));
NONTopsisNegCrispSeparationWALLAlpha = zeros(nCnpt,length(alphaVal));

for i=1:nCnpt
    for j=1:length(alphaVal)
        NONTopsisPosCrispSeparationWALLAlpha(i,j) = (1-
alphaVal(j))*NONTOPSISPosSeparation{i}(1) +
alphaVal(j)*NONTOPSISPosSeparation{i}(2);
    end
end

```

```

        NONTopsisNegCrispSeperationWALLAlpha(i,j) =
alphaVal(j)*NONTOPSISNegSeperation{i}(1) + (1-
alphaVal(j))*NONTOPSISNegSeperation{i}(2);
    end
end

% Step 10 Calculate the closeness coefficients for each of the concepts
ClosenessCoefficientAllAlpha = zeros(nCnpt, length(alphaVal));
for i=1:nCnpt
    for j=1:length(alphaVal)
        ClosenessCoefficientAllAlpha(i,j) =
NegCrispSeperationWALLAlpha(i,j)/(NegCrispSeperationWALLAlpha(i,j)+PosCrispSeperatio
nWALLAlpha(i,j));
    end
end

ClosenessCoefficientAllAlphaNONTopsis = zeros(nCnpt, length(alphaVal));
for i=1:nCnpt
    for j=1:length(alphaVal)
        ClosenessCoefficientAllAlphaNONTopsis(i,j) =
NONTopsisNegCrispSeperationWALLAlpha(i,j)/(NONTopsisNegCrispSeperationWALLAlpha(i,j)
+NONTopsisPosCrispSeperationWALLAlpha(i,j));
    end
end

%We will use the ExpertConfidenceData to develop the crisp values from the expert
confidence value reported.
tempConf = 0;
AvgExpertConfidence = zeros(nCnpt,1);
AvgExpertConfidenceAlpha = zeros(nCnpt,1);
tempArr = zeros(length(alphaVal));

for i=1:nCnpt
    for e = 1:nExp
        tempConf = tempConf + ExpertConfidenceData{e}(i);
    end
    AvgExpertConfidence(i) = tempConf/nExp;

    AvgExpertConfidenceAlpha(i) = max(alphaVal([0:length(alphaVal)-
1]<=AvgExpertConfidence(i))));

    %Error case. Never happens
    if (AvgExpertConfidence(i)==5)
        AvgExpertConfidenceAlpha(i) = alphaVal(length(alphaVal));
    end

    tempConf = 0;
end

%calculate the closeness coefficients considering just one alpha value extracted
from reported expert confidence. The variables with non-TOPSIS are related to FVDUS
criteria

PosCrispSeperationExpertAlpha = zeros(nCnpt,1);
NegCrispSeperationExpertAlpha = zeros(nCnpt,1);

for i=1:nCnpt

```

```

    PosCrispSeparationExpertAlpha(i) = (1-
AvgExpertConfidenceAlpha(i))*PosSeparation{i}(1) +
AvgExpertConfidenceAlpha(i)*PosSeparation{i}(2);
    NegCrispSeperationExpertAlpha(i) =
AvgExpertConfidenceAlpha(i)*NegSeperation{i}(1) + (1-
AvgExpertConfidenceAlpha(i))*NegSeperation{i}(2);
end

PosCrispSeparationExpertAlphaNONTopsis = zeros(nCnpt,1);
NegCrispSeperationExpertAlphaNONTopsis = zeros(nCnpt,1);

for i=1:nCnpt
    PosCrispSeparationExpertAlphaNONTopsis(i) = (1-
AvgExpertConfidenceAlpha(i))*NONTOPSISPosSeparation{i}(1) +
AvgExpertConfidenceAlpha(i)*NONTOPSISPosSeparation{i}(2);
    NegCrispSeperationExpertAlphaNONTopsis(i) =
AvgExpertConfidenceAlpha(i)*NONTOPSISNegSeperation{i}(1) + (1-
AvgExpertConfidenceAlpha(i))*NONTOPSISNegSeperation{i}(2);
end

ClosenessCoefficientExpertAlpha = zeros(nCnpt,1);
for i=1:nCnpt
    ClosenessCoefficientExpertAlpha(i) = NegCrispSeperationExpertAlpha(i) /
(NegCrispSeperationExpertAlpha(i)+PosCrispSeparationExpertAlpha(i));
end

ClosenessCoefficientExpertAlphaNONTopsis = zeros(nCnpt,1);
for i=1:nCnpt
    ClosenessCoefficientExpertAlphaNONTopsis(i) =
NegCrispSeperationExpertAlphaNONTopsis(i) /
(NegCrispSeperationExpertAlphaNONTopsis(i)+PosCrispSeparationExpertAlphaNONTopsis(i)
);
end
%save the outputs
clearvars("ans", "e", "fileName", "i", "j", "tempArr", "tempConf", "tempLowLim",
"tempUpLim", "tempVar")
save(fullfile(folderPath, 'ClosenessCoefficientsOutput.mat'), "ClosenessCoefficientExp
ertAlpha", "ClosenessCoefficientAllAlpha");
save(fullfile(folderPath, 'ClosenessCoefficientsOutputNONTOPSIS.mat'), "ClosenessCoeff
icientExpertAlphaNONTopsis", "ClosenessCoefficientAllAlphaNONTopsis");
save(fullfile(folderPath, 'ClosenessCoefficientsALLOutput.mat'));
clear;

```

Appendix J –Questionnaire for Understanding Frugal Mindset

The following questionnaire was used for conducting semi-structured interviews with designers and decision-makers to understand the frugal mindset phenomenon. Details of the study are presented in Chapter 6.

Questionnaire and Protocol for Semi-Structured Interview

Protocol for the interview: The interviewer completed the following steps before starting the interview process:

- 1 Introduction of the interviewer
- 2 Participants were asked if it is ok to record the session?
- 3 Participants were told that the recording is only to remember and analyse the interview data, and will not be used for any other purpose or shared with anyone other than the core research group.
- 4 Participants were thanked for being part of the interview and sparing their valuable time.
- 5 Participants were told about the reason this interview is being conducted. The reasons are as follows:
 - a. To find out how designers can design successful solutions for the people and communities living in marginal contexts.
 - b. To get an understanding of how you were able to design a successful solution.
 - c. To understand the mindset required for developing products for people living in marginal contexts.
 - d. To understand the design process and the constraints in designing.
- 6 Participants were told the following details:
 - a. Approximately 30 to 60 minutes will be required to complete the interview.
 - b. No personally identifiable information other than any that is specifically required for the research will be collected.
 - c. This interview is strictly for academic and research purposes only. No part of the interview transcripts will be shared with anyone other than the core research group.
 - d. Researchers will be able to tell other designers how to design better and more successful products for marginal contexts based on the research data.
- 7 Participants were asked if they are willing to continue with the interview.
 - a. If Yes, interviewers proceeded with the questions; if no, participants were thanked, ending the interview.
- 8 Participants were asked if they have any questions, and the interviewer answered them?
 - a. Answer any question that they have.
- 9 After following the protocol, the following questions were asked.

Objective	Questions	Follow-up Questions
Introduction	Please tell us your name. Please tell us your educational qualifications. How many years of experience do you have? How many projects have you done related to the underprivileged? How have you been associated with the company or the project?	
Basic of the product and customers	Could you please tell us a little bit about your product or solution?	What services do you offer along with your solution?
	How does your solution serve underprivileged people?	Do you consider your target customers to be part of the 'bottom of the pyramid'? Why?
Pre-Decisional	What made you interested in becoming part of the project?	
	What were the problems that you wanted to solve?	
	Did you think about any other ways to solve the problem?	How did you get the ideas?
	What made you sure that your solution would work?	
	Did you do any studies before you started developing the solution?	If Yes, Why was the study done? If No, Why did you think no study was required?
Pre-Actional	Before starting the project, what did you think would be the most difficult part of the project?	
	How did you plan the design process?	Why did you think this was a good plan?
	When you were designing, did you ever doubt if the solution will work?	What made you go on?
Actional	How would you suggest a new designer approach a similar project?	
	When did you become sure that the solution would be successful?	
Post-Actional	What was actually the most challenging part of the development?	How did you overcome it?
	Do you think the product will be a long terms success?	Why?
Conclusion	What advice would you give a new designer who wants to work on a similar problem?	Are there any things he/she should not do?
	In Retrospect, would you do anything differently?	Do you have anything else you wish to share?
	Do you have any questions for us?	
	Thank you very much for helping us.	
	We will remain in touch with you and will surely update you with the outcomes of the research.	
	Would you mind if we contacted you again with any queries about your answers at a later stage?	
	Thank you.	
	Any recording is stopped.	

Appendix K – Design Activities in the FLOW Toolkit

Table K.1 shows the Design Activities considered in the FLOW toolkit. These Design Activities were developed based on the FDC frameworks developed in this research. See Chapter 7 for details on the development of the list.

Table K.1: Design Activities for the FLOW toolkit and Canvases designed for each activity.

FDC framework phases	Title and description of Design Activity	Keywords relevant for the Design Activity	Canvases designed for supporting the Design Activity. (reference number in FLOW toolkit)
Initiation	Project Initiation: The initial design brief is collected from the project initiators and analysed. A design team is formed to work on the brief. Team members and the initiators discuss and understand each other's motivations for doing the project.	Initial Brief, Preliminary Field Visit, Team Formation, Motivations, Timeline, Scope	<ul style="list-style-type: none"> • Probe for understanding individual motivation (C01)
Initiation	Project Plan Creation: The team reviews the brief with initiators and seeks clarification if any. The team and initiators then collaboratively develop a vision, mission, objectives and goals for the project. The project complexity is evaluated based on the decided goals, and a project plan is created.	Vision and Mission, Aim and Objectives, Project plan, Project complexity, Milestones	<ul style="list-style-type: none"> • Probe and Template for defining Mission and Goals (C02) • Mission Statement Template (C03) • Tool for evaluating project complexity (C04) • Poster for recording project milestone (P1)
Context Understanding	Define the Wicked Problem: The design team defines a problem domain and the wicked problem to solve. A systematic search is conducted to find relevant research and existing solutions in the problem domain. Insights from literature and existing solutions are extracted and discussed.	Problem domain, Literature search, Existing solutions, Theory of change	<ul style="list-style-type: none"> • Tool for creating a preliminary Theory of Change (C05) • Probe and Template preliminary analysis of existing solutions (C06)

Context Understanding	Identify Stakeholders and Visionaries: The design team lists the stakeholders and visionaries for the project. Motivations of stakeholders are understood. A plan for the interviews is created. The team then contacts all stakeholders to get consent for participating in project activities.	Identify stakeholders, Understand motivations, Plan Interviews, Gather Consent	<ul style="list-style-type: none"> • Template and tool for recording and analysing stakeholder information. (C07) • Tool for Planning Interviews (C08) • Poster for recording Stakeholder Information (P2)
Context Understanding	Conduct and Analyse Interviews: The design team conducts face to face interviews with stakeholders and visionaries as planned. They then gather details about the context and assess stakeholder reactions to the project plan. Research data is then analysed to draw design insights, requirements and specific strategies to meet project goals. A report with the key findings is made.	Stakeholder interviews, Data collection, Design Insights, Requirements, Research report	<ul style="list-style-type: none"> • Prompt and Template for analysing interview data (C09)
Context Understanding	Plan Participatory Research: The design team identifies locations in context for conducting field visits and participatory activities. The team then brainstorms and develops activities and participatory exercises needed to understand the context. They then create a plan for the activities and develop the necessary tools, canvases, and collaterals to support them.	Participatory activities, Tools and canvases, Context boundary, Recruit participants	<ul style="list-style-type: none"> • Tool for defining and analysing the context boundary (C10)
Context Understanding	Understand User's Daily Lives: The design team conducts a series of user interviews and participatory exercises to understand the users' daily lives. The team then tries to understand the user's wishes, desires, aspirations, and the solution's impact. Possible solutions and shortcomings of existing solutions are uncovered.	User Interview, Participatory exercise, Wishes and Desires, Deep understanding, Insights	<ul style="list-style-type: none"> • Template and Prompt for Analysing User's Daily lives (C11)
Context Understanding	Understand Contextual Constraints: The design team conducts participatory exercises with users, stakeholders, and visionaries to understand the constraints based on the CEH framework. The team then identifies locations and entities which enable or mitigate these constraints and conducts field visits to these locations. Data is gathered and analysed to determine insights and strategies to mitigate or leverage the constraints.	Participatory exercises, Contextual constraints, Design strategies, CEH framework, Field visit	<ul style="list-style-type: none"> • Probe for identifying contextual constraints and mitigation strategies (C12)

Problem Definition	Analyse Research and Find Directions: The design team analyses and organises the findings from all prior research activities. The findings are collated, combined and clustered to identify key insights, requirements and design goals. The team then brainstorms and develops several design directions and broad level solutions. These directions are analysed, and criteria for measuring its success are discussed. One or more design directions is then selected.	Research Analysis, Insights, Design directions, Success Criteria, Capability Improvement	<ul style="list-style-type: none"> • Template for identifying and recording design directions (C13)
Problem Definition	Create Briefs and Report Outcomes: The design team analyses prior research outcomes and develops design briefs for product design, strategic design, service design, and dissemination parts of the holistic solution. The design insights, requirements, and strategies from prior research are collated and combined to generate the product's functions and features. The research insights are discussed with stakeholders	Design brief, Non-Tradeoff functions, Primary and secondary function, Product features, Research report	<ul style="list-style-type: none"> • Template for identifying and recording product requirements and features (C14) • Template for creating a report on the research outcomes (C15) • Poster for recording key design insights and requirements (P3)
Product Design Ideation	Analyse Existing Solutions: Existing solutions, concepts are collected and organised. The team then analyses these solutions and selects benchmarks which are then analysed more in-depth. The benchmark solutions are acquired, and their construction is understood using reverse engineering methods. Product performance in key technical specifications and other design insights are derived based on evaluating the benchmark solutions.	Existing solutions, Benchmark analysis, Reverse engineering, Target specifications	<ul style="list-style-type: none"> • Probe for Analysing Benchmark Solutions (C16) • Tool and Template for Identifying and analysing Technical Specifications (C17)
Product Design Ideation	Define Technical Specifications: The team collects the findings from prior research and benchmark analysis, specifically related to product design. Technical specifications for product performance are derived from the insights, requirements and previous research. The team then specifies an acceptable and adequate performance level for each technical specification. Testing methods for product concepts and measurement criteria for technical specifications are conceptualised.	Technical Specifications, Performance level, Testing methods, Measurement criteria	<ul style="list-style-type: none"> • No specific canvas
Solution Proposal Ideation	Strategic Analysis of Benchmarks: The design team reviews and analyses the value chain and stakeholder configurations of benchmark solutions. The effectiveness of the business model, service design and dissemination strategies used are studied. The team then develops specific insights and requirements for business model design, service design, and disseminating a holistic solution.	Benchmark solution, Strategic analysis, Value chain, stakeholder configuration	<ul style="list-style-type: none"> • No specific canvas

Solution Proposal Ideation	Plan Participatory Ideation: The design team reviews prior research outcomes and collates relevant findings for participatory ideation sessions. Insights are clustered and grouped to develop specific ideation briefs and exercises for participatory sessions. The team then plans several participatory activities to ideate the solution's product design, business model, service design and dissemination aspects. Canvases and tools are developed for facilitating participatory sessions.	Ideation tools, Participatory exercises, Product design, Business model, Service Design, Dissemination	<ul style="list-style-type: none"> • No specific canvas
Product Design Ideation	Product Design Ideation: The design team invites users, stakeholders and visionaries for a participatory ideation session. The team executes and facilitates participatory exercises to develop new ideas for product design. The members generate new ideas for the product using the design briefs, tools, and canvases developed earlier. The design team and participants collaboratively select promising ideas for further development.	Idea generation, Idea Selection, Iteration, Participatory exercises	<ul style="list-style-type: none"> • Template for Recording Design Ideas and Insights (C18) • Poster for Recording key design ideas (P4)
Solution Proposal Ideation	Solution Proposal Ideation: The design team gathers participants and conducts exercises for generating new ideas for a business model, services and dissemination of the product concept. Participatory activities are used to develop ideas to support the product throughout its life cycle. The team then organises and clusters connected ideas which can work together holistically. Promising idea sets are selected for further development.	Ideation, Business model, Service design, Dissemination, Product life cycle	<ul style="list-style-type: none"> • Prompts for generating strategic Ideas related to Business model, Service Design and Dissemination of the Solution (C19)
Solution Proposal Ideation	Evaluate and Select Concept: The design team and participants review and select thematically related ideas. These ideas are then combined into concepts of a holistic solution. Several such concepts are created, combining multiple ideas related to product design, business model, service design and dissemination. The team and participants evaluate the concepts and select one for further development.	Combine Ideas, Iteration, Holistic Solution concept, Idea evaluation	<ul style="list-style-type: none"> • No specific canvas
Product Design Definition	Define Product Architecture: The team reviews the product functions, selects working principles, and creates necessary proof-of-concept models. They then develop a schematic for the critical functions and identify essential parts and components. Parts and components are then grouped into modules, and a rough geometric layout of the product is created. The resulting architecture is then analysed, and critical interfaces between modules are identified.	Working principles, geometric layout, product schematics, Modules, Interfaces	<ul style="list-style-type: none"> • Prompts for Developing Effective Product Architecture and Interfaces. (C20)


Product Design Definition	Develop Product Embodiment: The design team selects an appropriate product architecture schematic and refines it to suit the context. The team then starts the development of various parts, components, modules and interfaces. The product embodied is then evaluated using engineering design methods and frugal design guidelines. The product embodiment is modified and iterated as necessary.	Parts, Components, Modules, Assembly, Creative engineering, Iteration	<ul style="list-style-type: none"> • Prompts for Developing Frugal Product Design and Embodiment Design (C21)
Product Design Definition	Product Prototyping: The design team reviews the product embodiment and finalises the design of critical modules. The team then develops suitable mockups and prototypes for testing the product functionality, feasibility, viability and desirability. Specific prototypes are designed for use in a participatory evaluation session. The team then reviews prior work to develop a plan for participatory testing and evaluation.	Prototype for X, Mockups, Testing plan, Participatory Evaluation	<ul style="list-style-type: none"> • No specific canvas
Solution Proposal Definition	Develop Service Design: The team reviews the solution proposal ideas generated in prior exercises and outlines the aspects related to service design. The team then develops and details the services needed for supporting the product throughout its life cycle. The team conceptualises the service policies, touchpoints, evidence and other service artefacts. The team then plans activities for evaluating the service concepts in a participatory session.	Service design concept, product life cycle, Service evidence, Touchpoints, Artefacts	<ul style="list-style-type: none"> • No specific canvas
Solution Proposal Definition	Develop Dissemination Strategies: The design team develops an appropriate brand identify and conceptualises activities required for building brand trust in the context. The team also details the strategies needed for distributing the solution in the context. Preliminary communication and branding materials are created and prototyped. Finally, the team plans activities for the participatory evaluation of the dissemination strategies.	Brand Identity, Marketing material, Training programs, Distribution channels, Packaging	<ul style="list-style-type: none"> • Prompts for Branding, Distribution, Dissemination and Training Strategies (C22)
Solution Proposal Definition	Detail Financial Strategy: The team starts by reviewing the stakeholder interactions and understands the cash flows. The team then creates projections and cost estimates for the solution's life cycle. Revenue models and investment calculations are developed if needed. The team then conceptualises the payment models and income generation opportunities. Participatory activities are then planned to evaluate the payment models and income opportunities.	Cost estimates, Financial projections, Break-even analysis, Payment models, Income opportunities	<ul style="list-style-type: none"> • Template and Tool for creating a stakeholder configuration and understanding financial flows. (C23)

Solution Proposal Definition	Participatory Evaluation of Solution Proposal: The team collects (or develops) activities for participatory evaluation of solution proposal and invites the stakeholders for the session. The complete solution, including the product, is simulated and evaluated in the context if possible. The team members facilitate the participatory session and document the outcomes. The team then reflects on the participatory exercises and plans the necessary modifications.	Simulated solution, Collaborative evaluation, Participatory activities, Iterations and modification	<ul style="list-style-type: none"> • No specific canvas
Proposal Formulation	Solution Proposal Documentation: The design team collects and organises prior outcomes and creates a detailed report on the solution proposal's development. The team then creates communication materials, brochures, pitch documents and other media for downstream development activities. The team also updates the technical documentation.	CAD, Control drawings, Product communication, Technical documentation, Reports	<ul style="list-style-type: none"> • No specific canvas
Downstream Planning	Initiate Downstream Development: The team discusses outcomes with project promoters and initiators and decides work for further development and pilot tests. Activities related to engineering optimisation and manufacturing are initiated. The team also initiates activities related to intellectual protection, agreements, investment or grant proposals. The team shares the final reports and outcomes with all the stakeholders and participants in the project.	Manufacturing plan, Pilot test, Intellectual property, Grant proposal, Investment, Final report	<ul style="list-style-type: none"> • Template and Prompt for Developing a design report and Reporting the overall outcomes (C24).

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Appendix L – Images from FLOW- Frugal Solutions Workflow Toolkit

The following images show some parts of the FLOW Toolkit. The details of synthesis and preliminary evaluation of the toolkit are discussed in Chapter 7. The complete FLOW Toolkit can be accessed from the link¹: <https://qr.go.page.link/CODpK>. The following images are from the **FLOW workbook**:



The image shows a 'Table of Contents' page from the FLOW workbook. The page is titled 'Table of Contents' and features a list of sections with corresponding page numbers. The sections are: 'What is FLOW?' (2), 'Who is FLOW for?' (6), 'How to use FLOW?' (10), 'Parts of FLOW.' (14), 'The FLOW workbook' (15), 'FLOW posters' (16), 'FLOW Canvases' (20), 'FLOW cards' (22), 'Before we begin.' (24), 'Project Complexity' (25), 'The FDC framework' (28), 'Context Evaluation Hierarchy' (34), 'Concluding thoughts.' (40), 'UNDERSTANDING Phase' (43), 'IDEATION Phase' (95), 'CONCEPTUALISATION Phase' (119), and 'FINALISATION Phase' (143). The page number 'vii' is located at the bottom right of the table.

What is FLOW?	2
Who is FLOW for?	6
How to use FLOW?	10
Parts of FLOW.	14
The FLOW workbook	15
FLOW posters	16
FLOW Canvases	20
FLOW cards	22
Before we begin.	24
Project Complexity	25
The FDC framework	28
Context Evaluation Hierarchy	34
Concluding thoughts.	40
● UNDERSTANDING Phase	43
● IDEATION Phase	95
● CONCEPTUALISATION Phase	119
● FINALISATION Phase	143
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Figure L.1: The Index page from the FLOW workbook. The foundational information is provided till page 40, after which the sections include the Design Activities for each phase of the FDC framework.

¹ The link leads to a cloud storage provider (Google Drive). Any warnings can be safely ignored.

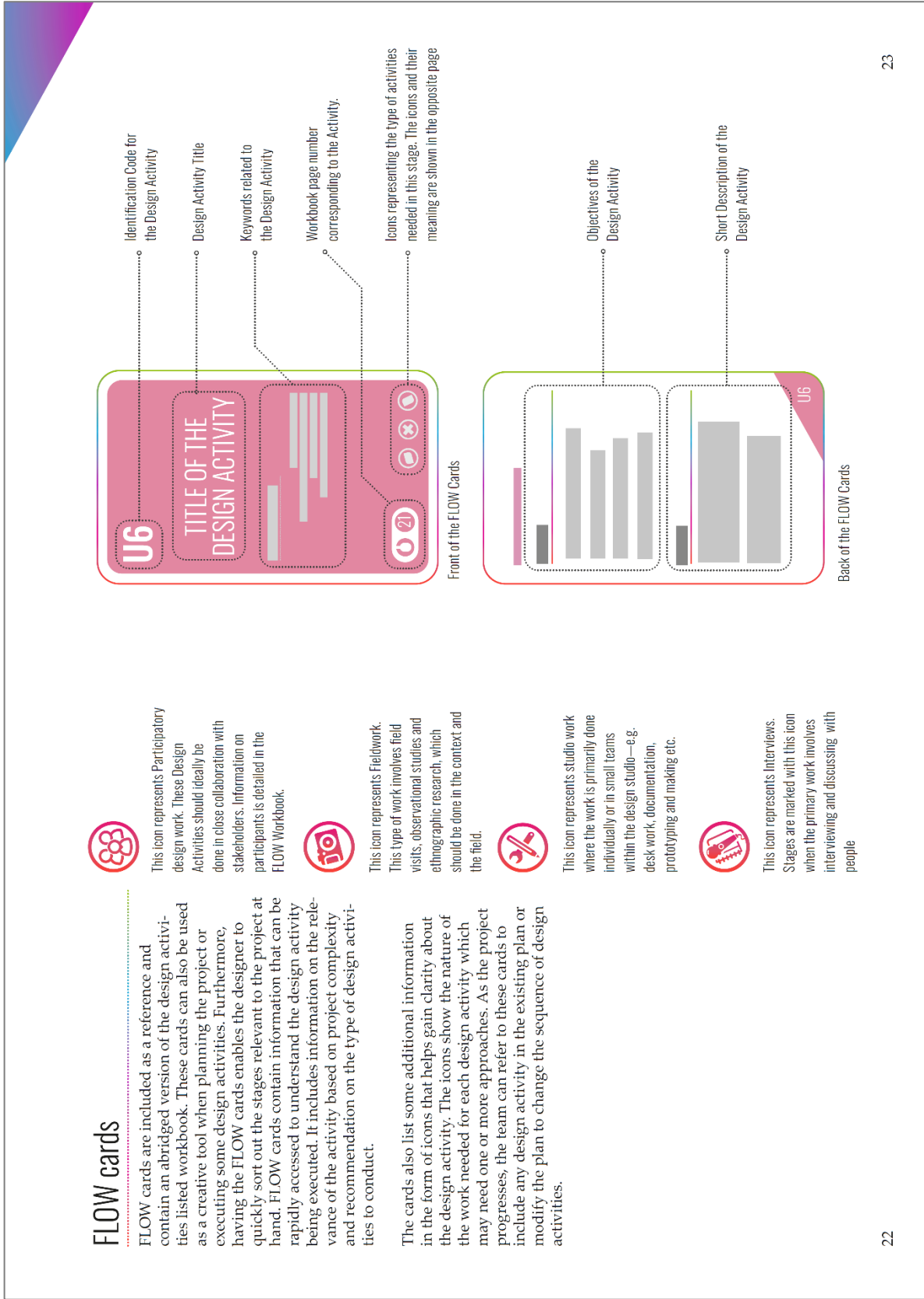


Figure L.2: A Page spread from the introduction section of the FLOW workbook discussing the FLOW Cards.

CREATE A PROJECT PLAN

Objective

- Clarify the project brief.
- Develop vision and mission statements.
- Evaluate project complexity.
- Plan project timeline and scope.

Design Activity

The team reviews the design brief with project initiators and seeks clarifications if any. The team and initiators then collaboratively develop the vision, mission, objectives and goals for the project.

The project complexity is evaluated based on the decided goals, and a project plan is created. Milestones and go-no-go review points are chosen. The FLOW poster P1 is used to display the final goal and objectives are in the design studio.

**TIME AND EFFORT**

One or more discussion sessions with project stakeholders may be needed. Some documentation work may be needed.

**PARTICIPANTS**

Primarily the design team and project initiators. Other stakeholders can be included if required.

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CREATE A PROJECT PLAN

Suggested Steps

1. Use Canvas C02 and C03 to develop a vision and mission for the project. Formulate a set of objectives and one criteria using which project success will be measured.
2. Use Canvas C04 for estimating the project complexity. C04 should be filled up collaboratively.
3. Use the FLOW cards and workbook to select the relevant Design Activities and collaboratively formulate a project plan.
4. Create a project timeline and decide on the significant milestones for the project. Fill up the poster P1 in a group.
5. Assign responsibilities to team members and initiate any project agreements.

**ADDITIONAL TOOLS**

Affinity mapping tools can be used when developing vision statements. Gantt Charts and Kanban cards can be used for project planning activities.

**CANVAS AND TOOLS**

Both Canvas C02 and C03 are for creating vision and mission statements. C02 is used individually, and then C03 is used to build consensus. C04 is used to understand the project complexity.

Mindset

When developing mission statements, affinity mapping can be used to identify key ideas. The project goal should be a measurable one that can be evaluated at the end of the project. Canvas C02 should be filled individually and discussed with the group. After this critical discussion, C03 should be filled in consensus with the whole team. C04 should also be filled collaboratively after considering all known aspect of the project.



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Figure L.3: The two-page spread of the first Design Activity in the FLOW workbook.



Figure L.4: Some pages from the different sections of the FLOW workbook showing the colour codes followed for Design Activities in the Ideation and Conceptualisation phases of the FDC framework.

C04 PROJECT COMPLEXITY EVALUATION

Project Complexity Evaluation Questions.

Agree Disagree

The business model followed by existing solutions is ambiguous or atypical.

The user will not be able to use the solution without supporting services.

The user may need to make multiple payments or instalments to use or own the product.

The solution will be difficult to distribute and sell through typical shops and retailers.

It is improbable that the solution can be sold through small and local retail shops operated by one person?


The solution has to be significantly sustainable in all three dimensions of sustainability.

The product may have more than one primary function.

The product may need a regular refill of consumables to function correctly.

The construction of the product is significantly ambiguous right now.

Total number of 'Agree' and 'Disagree'



These questions should be answered after an initial assessment of the context. Use the project complexity evaluation to consider the Design Activities needed in the project.

Project Complexity Evaluation Questions.

The solution to this problem has the potential to change the whole design context significantly.

The change that the solution may bring to the user's lives is ambiguous.

The exact type of product which could solve this problem is unclear.

There are very few existing solutions which solve a similar problem.

The team will have to conduct significant research before clearly understanding the constraints offered by the context.

There are legal, political, and socio-cultural issues which may undoubtedly affect the solution.

It will be impossible to understand the impact of the solution without doing pilot tests in the actual context.

It is ambiguous which of the parameters of CEH will have the most impact on the solution when its in use. (refer page 30 of FLOW process guide)

The solution will most likely need a unique business model that is atypical in the context.

Total number of 'Agree' and 'Disagree'


- The project may be of **low complexity** if less than 6 'Agree' boxes are ticked.
- The project may be of **medium complexity** if 6 to 11 'Agree' boxes are ticked.
- The project may be of **high complexity** if more than 11 'Agree' boxes are ticked.

The project complexity may change as new information is uncovered during the project.

Figure L.5: The FLOW Canvas for estimating the project complexity.

C07 KNOW YOUR STAKEHOLDERS

This canvas is used as a template for analysing the stakeholders of the project. For each stakeholder, note down the details and discuss the project and its impact on the overall solution. It is essential to take consent before deciding to include a stakeholder in the project.



Name: *SHORT NAME OF THE STAKEHOLDER*

Is the Stakeholder and Entity or an Individual? Individual. Entity

NAME
CONTACT
OTHER DETAILS

This stakeholder can be categorized as...

User of the Solution Initiator or Promoter Visionary in the context.
 Knowledge stakeholder Production stakeholder Service stakeholder
 Market stakeholder Finance stakeholder Administration Stakeholder
 Other

MOTIVATION

The reason this stakeholder would want to be part of this project OR, would want to see the project succeed is...

BECAUSE...

Type of Motivation
 \$ Income or Financial gain
 👑 Recognition or Respect
 📖 Knowledge or Learning
 🏠 Affiliation or Social belonging
 ? Others

This stakeholder can be categorized as...

Primary Stakeholder Secondary Stakeholder Tertiary Stakeholder


Select this entity as a key stakeholder? Yes No

\$ Income or Financial gain 👑 Recognition or Respect 📖 Knowledge or Learning 🏠 Affiliation or Social belonging ? Others

64 This canvas can be downloaded from the link or drawn by hand if needed.

C17 BENCHMARK SOLUTION ANALYSIS

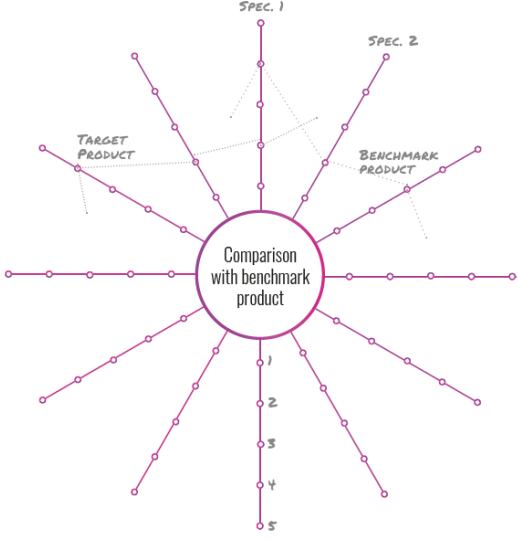
This canvas is a template for analysing the technical specifications of benchmark products and its qualitative comparison with a new concept. Note the key technical specifications of the benchmark product and the new product concept for a qualitative comparison.



Name of Benchmark Product: *SHORT NAME OF THE PRODUCT*

KEY TECHNICAL SPECS.

TECHNICAL SPECIFICATION NO. 1	VALUE AND UNIT
WEIGHT OF PRODUCT	25 KG
OUTER CASING MATERIAL	ABS PLASTIC

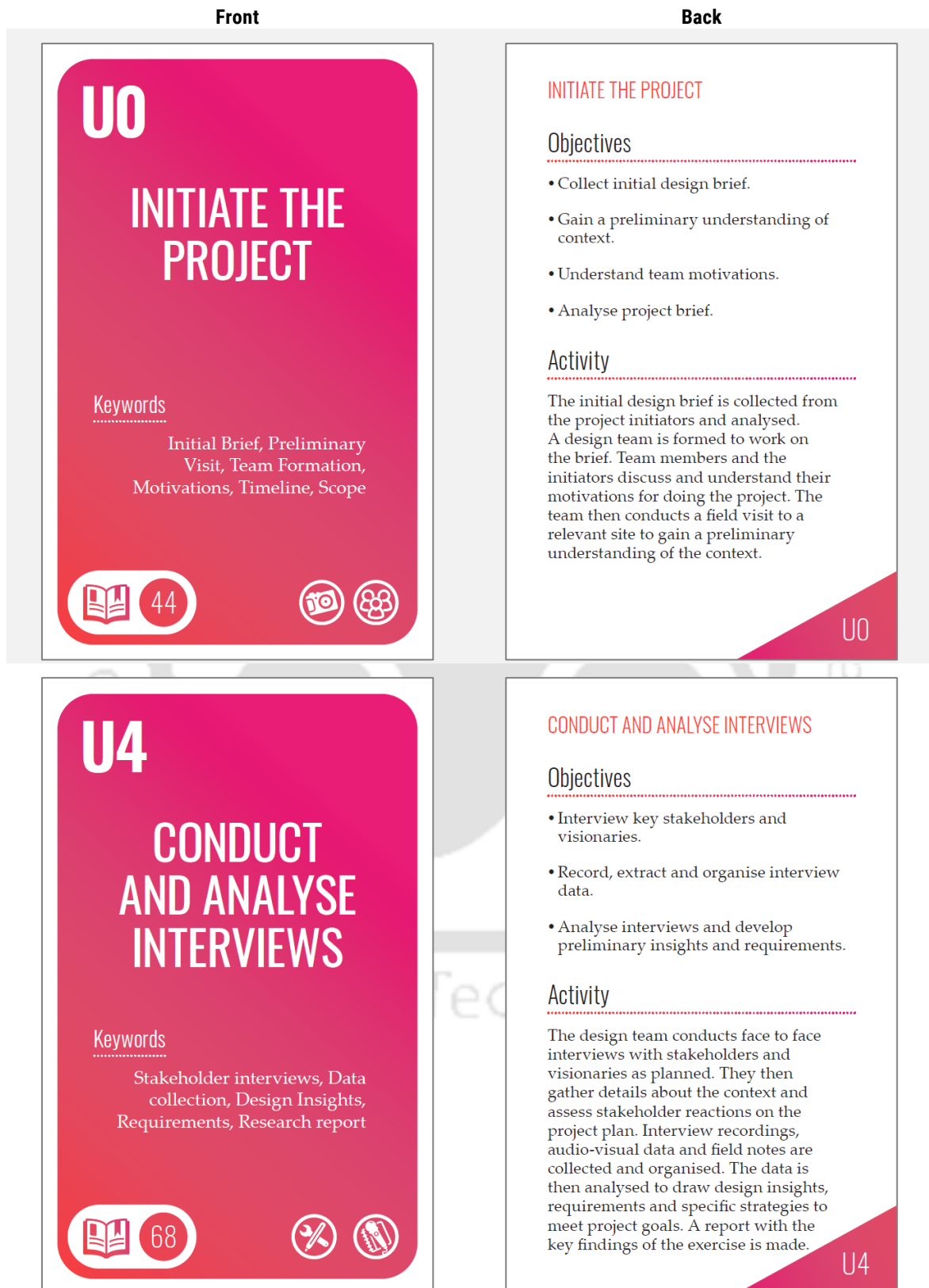


The diagram is a radial comparison tool. At the center is a circle labeled 'Comparison with benchmark product'. Five lines radiate from this center to five points labeled 'SPEC. 1' through 'SPEC. 5'. Two additional lines radiate from the center to 'TARGET PRODUCT' and 'BENCHMARK PRODUCT'. The lines are connected by small circles, forming a network of comparison points.

100 This canvas can be downloaded from the link or drawn by hand if needed.

Figure 1.6: Some FLOW Canvases from the toolkit shown to illustrate the different types used in the toolkit.

Following are some images showing the FLOW Cards in the toolkit.



C3

STRATEGIC ANALYSIS OF BENCHMARKS

Keywords

Benchmark solution, Strategic analysis, Value chain, stakeholder configuration



104



STRATEGIC ANALYSIS OF BENCHMARKS

Objectives

- Analyse strategic aspects of benchmark solutions.
- Understand the value chain and stakeholder configuration of solutions.
- Develop design requirements for business models, services and dissemination.

Activity

The design team selects a set of existing solutions as benchmarks for the strategic aspects of design. They review and analyse the value chain and stakeholder configurations of these solutions. The effectiveness of the business model, service design and dissemination strategies used are then studied. The team then develops specific insights and requirements for business model design, service design, and disseminating a holistic solution.

C3

C6

SOLUTION PROPOSAL IDEATION

Keywords

Ideation, Business model, Service design, Dissemination, Product life cycle



112



SOLUTION PROPOSAL IDEATION

Objectives

- Conduct participatory exercises to generate ideas for Business model design, Service Design and Dissemination of the solution.
- Organise and select promising strategic ideas for further development.

Activity

The design team gathers participants and conducts exercises for generating new ideas for a business model, services and dissemination of the product concept. Participatory activities are used to develop ideas to support the product throughout its life cycle. The team then organises and clusters connected ideas which can work together holistically. Promising idea sets are selected for further development.

C6

D7

PARTICIPATORY EVALUATION OF SOLUTION

Keywords

Simulated solution,
Collaborative evaluation,
Participatory activities,
Iterations and modification



PARTICIPATORY EVALUATION OF SOLUTION

Objectives

- Conduct participatory activities for evaluating the solution.
- Simulate the solution in context and evaluate collaboratively.
- Reflect on participatory activities and plan modifications.

Activity

The team collects (or develops) activities for participatory evaluation of solution proposal and invites the stakeholders for the session. The complete solution, including the product, is simulated and evaluated in the context if possible. The team members facilitate the participatory session and document the outcomes. The team then reflects on the participatory exercises and plans the necessary alterations for the solution.

D7

F2

INITIATE DOWNSTREAM ACTIVITIES

Keywords

Manufacturing plan,
Pilot test, Intellectual
property, Grant proposal,
Investment, Final report



INITIATE DOWNSTREAM ACTIVITIES

Objectives

- Decide on further development activities and plan for pilot tests.
- Initiate activities for IP, optimisation, manufacturing and investments.
- Plan the work related to initial deployment, pilot testing and impact assessment.

Activity

The team discusses outcomes with project promoters and initiators and decides to work for further development and pilot tests. Activities related to engineering optimisation and manufacturing are initiated. The team also initiates activities related to intellectual protection, agreements, investment or grant proposals. The team develops plans for the initial deployment and impact assessment of the Solution Proposal.

F2

-X-

Appendix M – Questionnaire for Preliminary Evaluation of the FLOW Toolkit

The Survey questionnaire used for preliminary evaluation of the FLOW toolkit is shown in Table M.1. Chapter 7 discusses the development and use of the questionnaire for understanding the Usability and 'Implementability' of the FLOW toolkit.

The questionnaire is divided into four parts. The first part (till question 3) covers the basic information about the respondent. The second part (question 4) lists the ten adapted questions from a Systems Usability Scale Questionnaire [1]. The third part is based on the "GuideLine Implementability Assessment (GLIA) Framework" [2]. Finally, questions 6 and 7 are for comparative evaluation of the FLOW toolkit with some known tools and existing processes followed by respondents.

As is common practice [1], the SUS questionnaire was adapted to suit the evaluation of the FLOW toolkit as shown below (bold words replaced the words in the bracket that were part of the original questions):

1. I think that I would like to use this **toolkit** (*system*) frequently.
2. I found the **toolkit** (*system*) unnecessarily complex.
3. I thought the **toolkit** (*system*) was easy to use.
4. I think that I would need the support of a technical person to be able to use this **toolkit** (*system*).
5. I found the various **features** (*functions*) in this **toolkit** (*system*) were well integrated.
6. I thought there was too much inconsistency in this **toolkit** (*system*).
7. I would imagine that most **designers** (*people*) would learn to use this **toolkit** (*system*) very quickly.
8. I **think that** (*found*) the **toolkit** (*system*) would be very cumbersome to use.
9. I feel (*felt*) very confident **that I'll be able to use** (*using*) the **toolkit** (*system*).
10. I needed to learn a lot of things before I could get going with this **toolkit** (*system*).

The chosen characteristics from the GLIA framework used for creating implementability related questions were as follows:

- **Decidability:** Can a reasonably experienced designer understand and agree on what to do with the toolkit?
- **Executable:** Are sufficient details provided to allow a designer to perform the Design Activities?
- **Presentation and Formatting:** Are the Design Activities structured and easy to understand?
- **Flexibility:** Does the toolkit sufficiently allow a designer to interpret its steps? Alternatively, Does the toolkit sufficiently allow for modification, updates and changes to suit the needs of a designer.

- **Apparent Validity:** Does the toolkit supports and facilitate what the designer wishes to do?
- **Measurable Outcomes:** Can the designer identify, measure and track the effect of implementing the tool?
- **Effect on Process:** Can the tool be used without significantly changing existing working methods?
- **Novelty:** Does the toolkit facilitate new and unconventional thinking, behaviour and methods?

The final survey questionnaire is shown below:

A preliminary survey of FLOW: The Frugal Design Workflow Toolkit

We are conducting a preliminary study on the ease of use and Implementability of a toolkit for designing Frugal Solutions in marginal contexts. The toolkit was developed to support design projects in socially oriented design organizations and academic institutions. Using this toolkit, designers can design Frugal products for marginal contexts.

The toolkit can be accessed from the link: qrqo.page.link/CQDpK

Please review the toolkit found in the link and answer the questions given below.

There are three parts to the toolkit, the FLOW workbook, FLOW cards and The FLOW posters. The FLOW workbook is the main component of the toolkit and contains multiple "Design Activities" that produce the necessary outcomes for creating frugal solutions. These Design Activities are presented in a structured format from page 44 onwards in the FLOW workbook. Designers can create a structured plan using these Design Activities and execute a Frugal Design Process.

Furthermore, we have included a set of 'Canvases' that can help execute various Design Activities. The Canvases work as probes, thinking and visualization aids, templates, and prompts to help the design team work efficiently. The Canvases can be found from page 44 onwards in the FLOW workbook.

The initial part in the FLOW workbook describes the various parts of the tool and how it should be used. We recommend you start there and then review the various Design Activities and Canvases before answering the questions.

Thank you for agreeing to be part of this survey. We will not be collecting any personal information here. The outcomes of this survey will be used to improve the toolkit further and for future research. You can download the toolkit from the link and keep it for reference or use it in your future projects. We would be extremely keen to hear from you if you use parts of the toolkit in your work. Please contact us if you have any queries or are interested in the FLOW toolkit.

Table M.1: Survey questionnaire for preliminary toolkit evaluation.

Objective	Topic	Questions
Basic Information	Who are you	<p>1. Choose an option that best describes you:</p> <ul style="list-style-type: none"> • I am an Undergraduate Design Student • I am a Post Graduate Design Student • I am a Postdoctoral Researcher in Design • I am a Faculty Member • I am a Practicing Designer • I work in a Non-Profit Organization • I work in a For-Profit Organization • I work with a Government Organization • None of the above* <p>* Responses were not collected from respondents who selected the option.</p>
	Where are you from	<p>2. Where do you practice your profession? (Options: Africa, Asia, Caribbean, Central America, Europe, Oceania, South America)</p>
	Experience	<p>3. How many projects related to underprivileged social scenarios have you been part of? (Options: 1,2,3,4, 5 or more, None*)</p> <p>* Responses were not collected from respondents who selected the option.</p>
Usability Assessment	SUS Questionnaire	<p>4. Please read the statements below and provide your answer on the given scale. (1= Strongly Disagree to 5= Strongly Agree)</p> <ol style="list-style-type: none"> 1. I think that I would like to use this toolkit frequently. 2. I found the toolkit unnecessarily complex. 3. I thought the toolkit was easy to use. 4. I think that I would need the support of a technical person to be able to use this toolkit. 5. I found the various features in this toolkit were well integrated. 6. I thought there was too much inconsistency in this toolkit. 7. I would imagine that most designers would learn to use this tool very quickly. 8. I think that the toolkit would be very cumbersome to use. 9. I feel very confident that I'll be able to use the toolkit. 10. I needed to learn a lot of things before I could get going with this toolkit.
Implementability Assessment		<p>5. Please read the statements below and provide your answer on the given scale.</p>
	Decidability	<p>1. I understand how to use this toolkit.</p>
	Executability	<p>2. I think the toolkit contains sufficiently detailed instructions for its use.</p>
	Presentation	<p>3. I found the written text easy to comprehend.</p> <p>4. I think there were too many jargons in the toolkit.</p>
	Flexibility	<p>5. I think parts of the toolkit can be easily modified for other purposes.</p>
	Apparent Validity	<p>6. I understood the theories behind the toolkit.</p> <p>7. I think the tool achieves its purpose.</p>

	Measurable Outcomes	8. I think a designer can create better outcomes when using this toolkit. 9. I think the positive effects of the toolkit can be easily measured.
	Effect on Process	10. I don't think any changes to existing processes are needed to implement the toolkit.
	Novelty	11. I think a designer can easily be creative while using this toolkit.
Comparative Analysis	Knowledge of existing toolkits	6. Which of the following design toolkits are you aware of? <ul style="list-style-type: none"> • "Design Kit: The Human-Centered Design Toolkit" by IDEO • "Collective Action Toolkit" by Frog Design • "Design for change in marginalized communities" by Paco Collaborative • None of the above
	Comparison with Existing Toolkits	7. Fill in the blank by choosing the most appropriate option. (Much Better, Slightly Better, Similar, not as good, Much Worse, can't decide) <ul style="list-style-type: none"> • The FLOW toolkit is _____ in comparison to other toolkits I know. • The FLOW toolkit is _____ in comparison to existing processes I follow.

References for Appendix M

- [1] A. Bangor, P. T. Kortum, and J. T. Miller, "An empirical evaluation of the system usability scale," *Int. J. Hum. Comput. Interact.*, vol. 24, no. 6, pp. 574–594, Aug. 2008.
- [2] R. N. Shiffman *et al.*, "The GuideLine Implementability Appraisal (GLIA): Development of an instrument to identify obstacles to guideline implementation," *BMC Med. Inform. Decis. Mak.*, vol. 5, no. 1, pp. 1–8, Jul. 2005.

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Appendix N –Images Related to Retrospective Analysis

The following sections show the images from the four design projects selected for the retrospective analysis study in this thesis. See Chapter 3 for the discussion on the projects.

N.1 - Project 1: Design of a vegetable vending station



Figure N.1: Various food and snacks vendors at the location. Observational studies and interviews were conducted with them to gather design requirements.



Figure N.2: Various vegetable vendors at location. Observational studies and short interviews were conducted with them for understanding the problem.

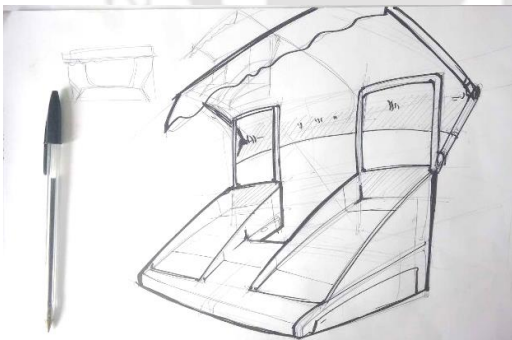


Figure N.3: One of the Design concepts developed. Several design concepts were created using various brainstorming methods.



Figure N.4: A CAD model for the finalised concept. Concepts were screened based on requirements and a final concept was detailed in a CAD application.

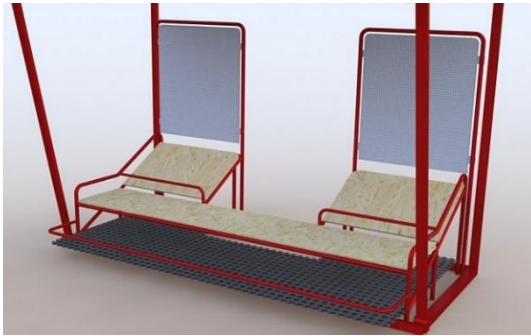


Figure N.5: Details of the CAD model. Detailed analysis of the final concept was done using CAD.



Figure N.6: Product Prototyping was done in collaboration with a local manufacturer.



Figure N.7: Prototype Evaluation. Prototype was evaluated based on the client requirements, basic ergonomics and technical specifications.



Figure N.8: Final prototype on location. The prototype was setup on location for preliminary evaluations and use.



Figure N.9: Final Prototype on location. The product was kept on location and vendors were allowed to use it free of cost for testing.



Figure N.10: Interview with vendors for evaluating the product. After a few days of use the vendors were interviewed to understand if the solution met their requirements. Several issues with the designs were recorded which were planned for the next iteration of the product.

N.2 - Project 2: Design of PoCT Device for PHCs



Figure N.11: A PHC near Guwahati. The team reviewed the existing infrastructure and conducted observational studies of the context.



Figure N.12: A nurse working in the PHC laboratory. The team interviewed the people and observed their work practices to identify design requirements and insights.



Figure N.13: A digital blood pressure monitor in a PHC. The team recorded the various PoCT devices and how they were used. Small scale hand held devices were common but larger diagnostic devices were rare.



Figure N.14: Prototype of a device designed by the center for Nano technology to demonstrate the technology. The design team analysed this device to implement its technology in a better solution.

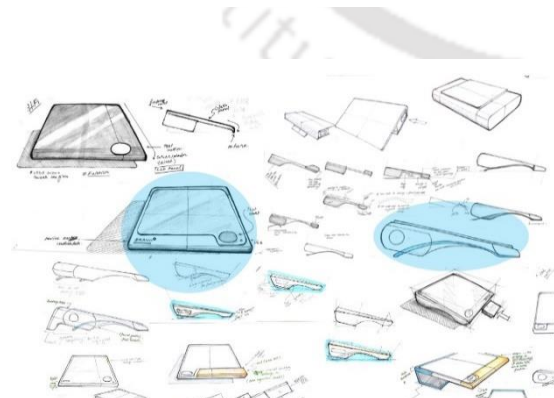


Figure N.15: Some of the design sketches for the product concept. Product concepts were sketched and discussed with the design team to arrive at a single design concept.



Figure N.16: CAD rendering of the finalized PoCT device concept. CAD models were developed for understanding the form, manufacturing and usability of

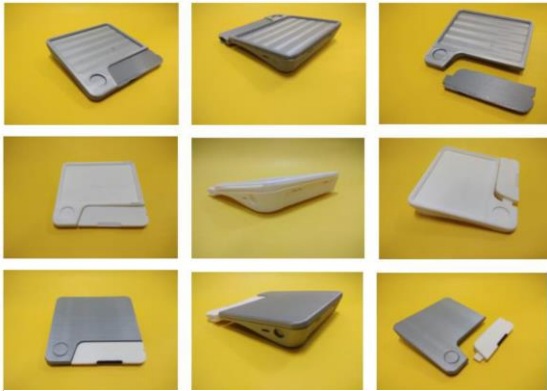


Figure N.17: Mockups of the finalized PoCT device concept. Mockups were tested with people in PHCs to understand their effectiveness.



Figure N.18: The user interface and details of the concept. The Black part of the device is the computational module and the blue part is the swappable module for conducting various diagnostic tests using paper strips.

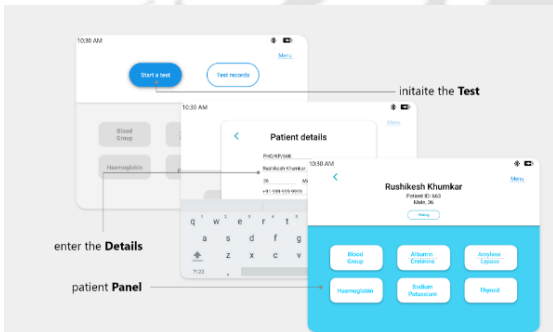


Figure N.19: UI screen for the device. The UI was based on mobile phone applications for familiarity and ease of

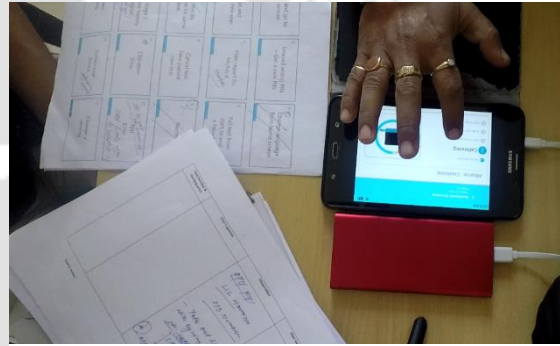


Figure N.20: The user interface and flow were tested through established UI evaluation methodologies.



Figure N.21: Functional prototype of the device used for testing and clinical trials.

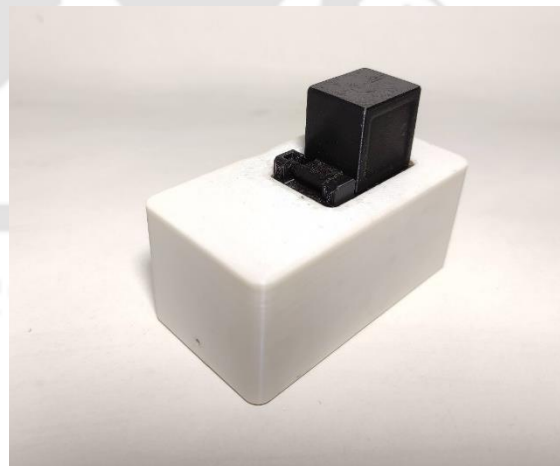


Figure N.22: A reagent mixing device designed as an auxiliary part of the primary product.

N.3 - Project 3: Design of Ginger & Turmeric Washing Machine



Figure N.23: A small-scale farmer showing newly harvested ginger.



Figure N.24: A lady farmer harvesting turmeric.



Figure N.25: The design team with collaborators and experts from an agricultural university.

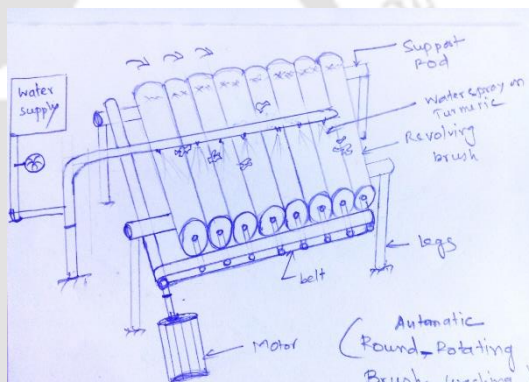


Figure N.26: One of the design concepts for washing newly harvested ginger and turmeric.



Figure N.27: A preliminary 'jugaad' prototype for the ginger turmeric washing machine. The team used readily available parts and components to create a prototype that enabled testing of the working principle.



Figure N.28: The internal view of the 'jugaad' prototype. Coir brushes were used to create a way to dislodge dirt from the produce.



Figure N.29: A jugaad prototype for a turmeric steamer made using existing products and



Figure N.30: Final concept for a turmeric steamer. The machine using simple manufacturing methods and materials for reducing product cost.



Figure N.31: CAD model of the first iteration of the ginger turmeric washing machine. CAD was used for detailing the product embodiment, finalizing product architecture and analysing it using DFM and DFMEA methods.

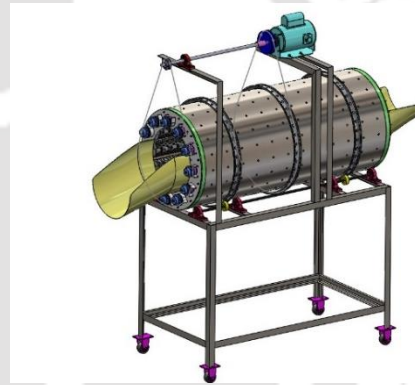


Figure N.32: Second iteration of the CAD. This iteration incorporated various findings from the engineering analysis.



Figure N.33: Final prototype of the washing machine. The prototype was developed in collaboration with a grassroots innovator. Frugal mindset of the innovator enabled significant reduction of cost.



Figure N.34: Image shows how the product use in a sharing-based PSS model. The product concept was appropriately modified to suit the specific requirements presented by the PSS model

N.4 - Project 4: Design of a Low-cost Bicycle Trolley for Washermen



Figure N.35: Washermen washing clothes in the Brahmaputra river bank.



Figure N.36: A Dhobi rinsing clothes. Most people cannot afford specialized machines for washing and rinsing clothes.



Figure N.37: A Dhobi using his feet to wash heavy clothes. People have skin problems due to such washing techniques.



Figure N.38: A Dhobi making bundles of washed clothes for transportation. Clothes are transported to different locations for drying.



Figure N.39: Dhobis readying washed clothes for transportation. Each bundle of wet clothes may reach around 80 kg.



Figure N.40: A Dhobi using his bicycle for transporting washed clothes. Bicycle are common and versatile modes of transport used by the people.

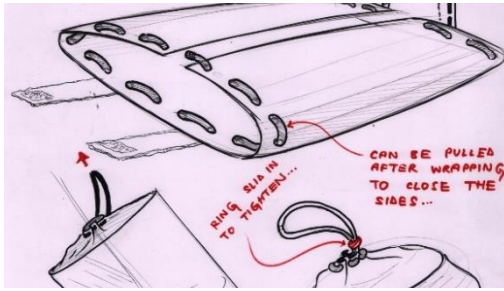


Figure N.41: Sketches of concepts designed for transporting washed clothes.

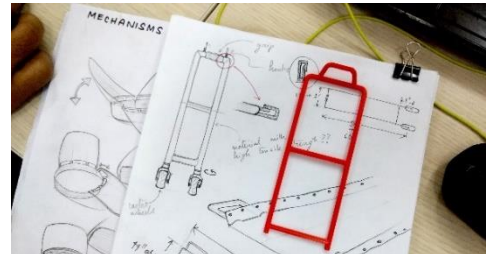


Figure N.42: Mockup model of the solution in development. Several mockups were developed before finalizing the design concept.



Figure N.43: First prototype of the product concept designed with a bag for bundling and transporting wet clothes.



Figure N.44: Final version of the product. collaborative evaluation of the solution led to the development of the modular product concept with multiple functionalities using attachments.



Figure N.45: Final product concept with attachments for storing dry clothes, a container for washing clothes and space for attaching an agitator



Figure N.46: Cutaway view of the concept showing a mechanism for rinsing of clothes.



Figure N.47: A rendering showing different configurations in which the final product can be used.



Figure N.48: Rendering of the final product showing how the product will be used in the context.

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List of Publications

Conference Paper 1: A framework for understanding the context and evaluating solutions in design for base of the economic pyramid, *Upadhyay, P., Punekar, R.M., Smart Innovation, Systems and Technologies, 2019, 134, pp. 769–779*

Conference Paper 2: Design Conceptualisation for Frugal Innovation, *Upadhyay, P., Punekar, R.M., FORE International Conference on Frugal Approach to Innovation, 2019*

Conference Paper 3: What Can Designers Learn from Failed Solutions in BOP Contexts? *Upadhyay, P., & Punekar, R. M. (2021). In Design for Tomorrow—Volume 3 (pp. 309-324). Springer, Singapore. (Awarded Distinguished Paper in ICoRD 2021 Conference)*

Conference Paper 4: "Contextualizing Sustainable Product-Service System Design Methods for Distributed Economies of India." *Banerjee, Sharmistha, Pankaj Upadhyay, and Ravi Mokashi Punekar. Designing Sustainability for All (2019): 270.*

Conference Paper 5: Co-designing with Visually Impaired Children, *Gupta, A., Fulfagar, L., Upadhyay, P., Smart Innovation, Systems and Technologies, 2021, 222, pp. 429–439*

Book Chapter 1: "Designing S. PSS and DE: New Horizons for Design." *Vezzoli, Carlo, Aine Petrulaityte, Sharmistha Banerjee, Pankaj Upadhyay, and Ravi Mokashi Punekar. Designing Sustainability for All (2021): 85.*

Book Chapter 2: S.PSS and DE in Practice, *Brenda Garcia Parra, Cindy Kohtala, Tatu Marttila, Aguinaldo dos Santos, Sandra Molina Mata, Fang Zhong, Nan Xia, Xin Liu, Jun Zhang, Sharmistha Banerjee, Pankaj Upadhyay, and Ravi Mokashi Punekar, In Designing Sustainability for All: The Design of Sustainable Product-Service Systems Applied to Distributed Economies (pp. 123-142). Springer Nature.*

Patents 1: PORTABLE AND MODULAR POCT DEVICE FOR RAPID MULTIPLE DIAGNOSTIC TESTS, Application No: 201931007736, Published, 29/03/2019

