



INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

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Programme of Study : Ph.D.
Thesis Title: SUSTAINABILITY ASSESSMENT OF ADDITIVE MANUFACTURING IN THE PRESENCE OF UNCERTAINTIES
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Thesis Submitted to the Department/ Center : Mechanical Engineering
Date of completion of Thesis Viva-Voce Exam : August 26, 2022
Key words for description of Thesis Work : 3D Printing, Additive Manufacturing, Build time, Cost estimation, Fused Deposition Modelling, Fuzzy Sets, Injection Moulding, Reliability, Selective Laser Sintering, Sustainability, Uncertainty

SHORT ABSTRACT

Additive manufacturing (AM) has gained enormous attention in the present digital era of sustainable manufacturing. It is popularly known as 3D printing and is one of the foundations of the fourth industrial revolution, i.e., Industry 4.0. Despite the unique advantages offered by AM, there is a hesitation in purchasing a 3D printer and including it in the manufacturing route. Although it is adopted by some industries, its rate of adoption is not high as predicted in the past. One of the main reasons is the concern of sustainability. AM needs to be cost-effective as well as sustainable to compete with traditionally established manufacturing technologies.

The focus of the thesis is to explore the sustainability of AM in the presence of uncertainties. Cost analysis is carried out to assess its competitiveness with other manufacturing processes. For this, first, a cost estimation model is proposed. The cost estimation model is developed based on several elements, i.e., material, operator, slicing and overhead cost. One of the most important steps in cost analysis is to determine the build time. Hence, as a part of cost estimation, build time estimation models of two popular AM processes, viz., selective laser sintering (SLS) and fused deposition modelling (FDM) are developed. The analytical models are developed based on machine kinematics and geometrical parameters. For SLS, the model is validated with data available in the existing literature. For FDM, the model is validated by conducting in-house experiments.

In practice, the parameters are often uncertain and vary with management policies. Hence, to take into account uncertainties, the deterministic cost model is converted into a fuzzy set-based cost model. For this, the uncertain quantities are treated as fuzzy variables and suitable arithmetic operations are performed. For simplicity, only linear triangular fuzzy members are used in this work for uncertain parameters. The low (l) and the high (h) estimates are assigned a membership grade of 0.5, whereas the most likely (m) estimate is assigned a membership grade of 1. The cost model is illustrated with examples. The cost of different parts fabricated by SLS and FDM are evaluated. First, the deterministic model is used to obtain the cost. Later, based on fuzzy set-based theory, the fuzzy cost estimates are obtained. The fuzzy cost of the parts is obtained in the form of a triplet. The working conditions of

a typical Indian factory is considered. Based on the information available in different internet sources and literature, cost parameters are quantified.

In the next part of cost analysis, SLS, a typical AM process is compared with injection moulding (IM) based on cost competitiveness considering the demand scenario. A cost model for IM is developed based on the information available in literature. The cost of IM is obtained by the algebraic summation of material, mould and processing cost. For SLS, the cost remains almost constant irrespective of the number of quantities albeit with some fluctuations. The design time associated with the designer and the slicing cost gets reduced with the number of quantities of the part. The processing cost per quantity (when the part is fabricated inside the machine chamber) is dependent on the build time per quantity. On the other hand, for IM, the cost per quantity decreases with an increase in the number of quantities. Based on the results obtained, it is seen that for some situations, some estimates of a process are lower and some are higher in comparison to the other process. For this, the concept of fuzzy reliability is used. The reliability estimates at different values of fuzzy cost are obtained. Based on the reliability estimates, a favourable manufacturing process is chosen.

The next part of the work delivers guidelines to an organization for assessing the utilization of AM. For this, a parameter, called utilization factor (U_f) is proposed based on total production time and available time. Based on U_f , the proper use of 3D printing is evaluated. U_f is incorporated in the cost model to understand its impact on the production cost. Typical cases of under, proper and over utilization of a 3D printer are discussed. The effect of U_f on the production cost for fabricating the same product and two different products are discussed. To compare two manufacturing processes, the unit cost and total production time for injection moulding (IM) and 3D printing are evaluated. Membership grades for suitability are provided based on cost and time. Assigning membership grades is subjective and may vary from organization to organization. The ability of AM to produce a product digitally reduces the requirement of human labour. This may give rise to unemployment amongst the labourers. To address such societal issues, a quantitative method to evaluate the labour penalty cost due to the reduction in employment is presented.

For environmental sustainability, approach for the estimation of energy consumption is discussed. Every AM process follows a similar pattern of layer by layer manufacturing, but the working principle varies for different processes. Hence, energy consumption also varies. The energy consumption models of SLS and FDM are described based on their working principle. The importance of different energy-consuming elements is described. The energy consumed for a single as well as multiple parts are evaluated. The results revealed that the mass and volume of a fabricated part give some indication about the energy consumption, but it also depends on part complexity. The energy consumption of the parts is used to estimate the energy cost and the amount of CO₂ emission. The energy cost is estimated based on the values of energy consumption and electricity rate. The amount of CO₂ emission in kg is estimated on an annual basis.

Overall, the work content of this thesis contributes to the sustainability evaluation of additive manufacturing processes. As the first pillar of sustainability, cost analysis of AM is carried out in the presence of uncertainties. Necessary guidelines are provided for industries willing to adopt AM. In the context of environmental aspect, energy consumption models are proposed where the role of energy consuming elements of AM based machines is described. Some aspects of social sustainability of AM and its impact on the society are discussed.