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Part Selection for Freeform Injection Molding: framework for development of a unique methodology

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Abstract. The purpose of this study is to provide an overview of a methodology, which will enable industrial end-users to identify potential components to be manufactured by Freeform Injection Molding (FIM). The difference between the technical and economic criteria needed for part selection for Additive Manufacturing (AM) and FIM will be discussed, which will lead us towards proposing a new methodology for part selection for FIM. Our proposed approach starts by identifying the most similar components (from end-user part libraries) to some reference parts, which can be produced by FIM. Identification will be followed by cluster analysis based on important factors for FIM part selection. As there are some interdependency between the factors involved in the clusters, some decision rules using Fuzzy Interference System (FIS) will be applied to rank the parts within each cluster using user-defined technical and economic criteria. Once the first set of potential FIMable parts have been identified, Design of Experiment (DOE) will be conducted to investigate which factors are most important and how they interact with each other to generate the desirable quality of the FIM parts. The DOE results will be validated in order to finetune the ranges of the parameters, which gives the best results. Finally, a predictive model will be developed based on the optimum feasible range of FIM parameters. This will help the end-users to analytically find the new FIMable parts without repeating the algorithm for the new parts.

Keywords: Freeform Injection molding, Additive Manufacturing, Part identification, Technical and economic factors.

1 Introduction

Injection molding is a widely used production technology, which is very cost effective for higher volumes of parts. For low-volume production, the lead time and costs of injection mold tooling are often a challenge, and molding investments may be difficult to recover. Moreover, the design freedom of plastic parts for traditionally made steel

tools are limited due to the necessity for “ejecting” the molded part from a rigid tool. For low volume production e.g. spare parts, Additive Manufacturing (AM) may be a more viable option [1]. But AM has multiple limitations, including slow process speed, poor dimensional accuracy compared to some conventional processes, rough surface finish [2], problems with process predictability and repeatability [3], restricted choice of materials [4], insufficient material properties, difficulties with material removal, high process costs and high energy intensity [5]. In particular, manufacturers find it difficult to justify AM as a direct alternative for injection molded parts, where performance requirements are often impossible to meet. Therefore, other advanced manufacturing technologies such as indirect 3D-printing [6] should be investigated.

2 What is Freeform Injection Molding (FIM)?

There are two main indirect 3D-printing technologies: 3D Printed Injection Molds (3DPIM), which is also known as “soft tooling” and FIM. 3DPIM (Fig. 1a) can address the prolonged lead-time and high costs associated to the design and manufacturing of mold tools. It has been shown that 3DPIM allows 80–90% production costs reduction as compared with a conventionally machined tool. Furthermore, the production lead-time will be reduced in the range of 60–70% compared to the time needed to machine mold tools [6]. 3DPIM are mostly produced by Polyjet 3D printing or Stereolithography (SLA) due to the high level of accuracy and good surface finish. 3DPIM tools are designed as split tools (the same as traditional mold tools) and, therefore, do not benefit from AM design freedom. The lifetime of the 3DPIM tools are limited due to the thermal shocks which will result in propagation of micro-cracks and failure [7]. Another limiting factor regarding 3DPIM is that printing materials are not temperature and pressure resistant and therefore, engineering materials cannot be processed. This is especially true where materials are brittle (e.g. in the case of metal or ceramic feedstocks) or where materials have a tendency to stick to the mold surfaces. The above-mentioned drawbacks with 3DPIM can be addressed by FIM, a patent pending concept, introduced by Danish company AddiFab. FIM uses single-use sacrificial closed-cavity mold inserts that are made with a soluble polymer.

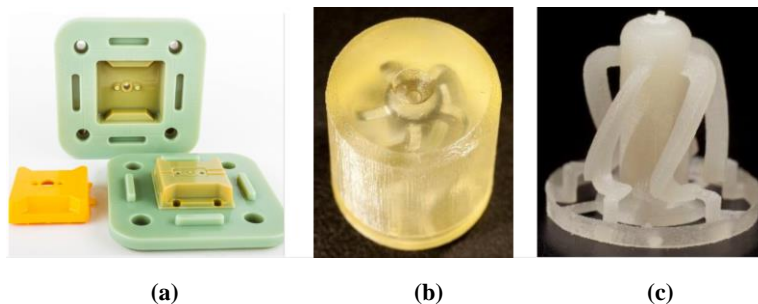


Fig. 1. a: 3D printed injection molds with Polyjet machine (image courtesy of Promolding), b: FIM mold with internal cavity, c: Injection molded part with FIM.

The FIM mold inserts are printed by a DLP machine in a patent-pending resin (IM 2.0 GP). The composition of IM 2.0 GP cannot be revealed due to confidentiality. The FIM mold (Fig. 1b) basically consists of a block of solidified resin with an internal cavity of the desired part (Fig. 1c). FIM can alleviate the shortcomings of both AM and injection molding by additively manufacturing low cost mold inserts of any complexity, which can then be used for producing low volume injection molded parts. FIM combines the short lead-times, low start-up costs and design freedom of AM with the versatility and scalability of injection molding. The key FIM objectives are to allow manufacturers to bring products to the market faster, cheaper and with lower risk, and to maintain the relevance of these products through easy customization and adaptations once they have been launched. The overview of the FIM value-chain can be seen in Figure 2.

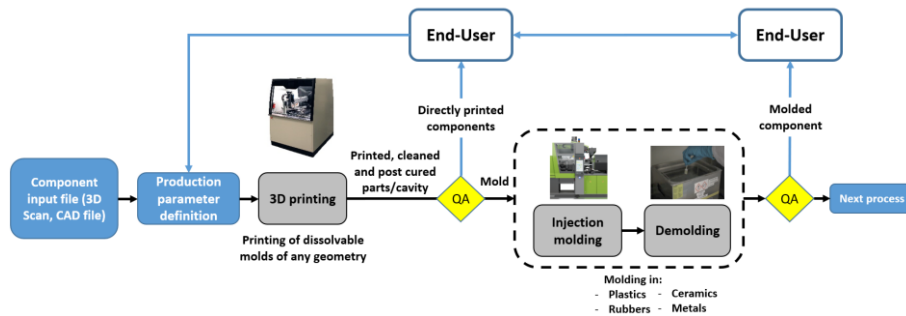


Fig. 2. High-level view of FIM process chain

3 Why is part selection important?

One key barrier for companies to adopt new technologies like AM or FIM is lack of understanding related to which parts can be produced using the technologies and difficulty in creating strong business cases for these parts [8]. Therefore, a number of methodologies and tools have been developed to support identification of parts suitable for manufacturing by AM [9]. Without such tools, it is very difficult and, in some cases, impossible for companies with large numbers of components to develop “short lists” of parts from their existing portfolio, which can be produced using AM technologies. Not only the part manufacturing companies have benefitted from the development of part identification tools for AM, the whole AM community has benefitted. More components identified or (re) designed for AM has meant increased AM volume, to the benefit of hardware (HW) vendors, materials vendors, service bureaus and other AM related services including software (SW). To the best of our knowledge, no standardized methodology has been developed to identify the most suitable components to be manufactured by FIM, which combines AM with IM. This makes it difficult for manufacturing companies with large numbers of components to build “short lists” of components from their existing portfolio that may be successfully manufactured using FIM. Therefore, development of a novel methodology to successfully screen and assess part candidates

for FIM is needed. Industrial manufacturers have large numbers of legacy products/spare parts would strongly benefit from part identification tool for FIM to quickly filter out those parts and components, which may be produced using FIM.

4 Part selection for AM

Selecting the suitable parts, which can be manufactured by AM pose significant challenges for manufacturers [8]. Company specific part characteristics, availability of data across multiple databases and in multiple forms, the need to consider multiple factors and the relationships of those factors with company specific objectives make it difficult to develop a universal methodology for part selection. The research by Lindemann et al. [10] and Knofius et al. [11] are the only ones available for parts selection for AM using multiple criteria. Lindemann et al. [10] outlined a methodology for part selection for AM using process primarily relying on expert assessments conducted in workshop mode. Knofius et al. [11] developed a methodology using Analytic Hierarchy Process (AHP) to identify the most suitable spare parts, which can be manufactured using AM. The output of the selection process was also validated with experts. Knofius et al. [11] did not present cost calculations for actual business case development of the potential parts. The above papers also did not discuss any common characteristics of the most suitable part candidates. Lack of availability of data and difficulty in developing a methodology has also forced some organizations to adopt only a bottom-up approach involving maintenance technicians' knowledge and experience to identify spare parts for AM. This empirical approach is the basis for commercially available tools developed for part selection for AM (e.g., Exalead, Cadenas and etc.). In these tools, the selection process starts with some manufacturable parts by AM as reference geometries. Accordingly, the most similar parts (from part library) to those reference geometries, will be identified and clustered based on user-defined criteria. Such an approach may not be suitable for an individual manufacturer, which is trying to identify parts, which are suitable for AM, for the first time without access to reference parts.

4.1 Factors considered for part selection for AM

Some of the factors used for part selection for AM [9,10,11] have been summarized in Figure 3. As it can be seen, these factors can be classified into two categories: technical factors and economic/supply chain parameters. In the study done by Knofius et al. [11] and Frandsen et al. [9], the focus has been on supply chain criteria for spare part selection for AM. In the work done by Lindemann et al. [10], the focus has been more on technical parameters needed for part selection for AM.

(Frandsen et al., 2019)		Knofius et al., 2016
High frequently used criteria	<ul style="list-style-type: none"> • Lead-time • Unit cost • Criticality • Annual dollar usage • Demand volume/rate/variability 	<ul style="list-style-type: none"> • Demand rate • Resupply lead time • Agreed response time • Remaining usage period • Manufacturing/ order costs • Safety stock costs • Supply risk • Number of supply options
Medium frequently used criteria	<ul style="list-style-type: none"> • Commonality • Substitutability • Repairability • Durability • No. of suppliers • Stockability • Warehouse space • Production availability • Perishability • Inventory cost • Lifecycle stage • Probability of failure • Demand predictability • Obsolescence • Last use date 	
Low frequently used criteria	Stock-out cost, part weight, part volume, availability of spares-consumables irreplaceability, scarcity, order size requirement, ordering cost, masked time, supply certainty, competition, payment terms, maintenance type, availability of technical specifications, failure type, machine category, spare part exchange time, exchange process complexity, special qualifications required, availability, and turnover rate	<p>Lindemann et al., 2015</p> <ul style="list-style-type: none"> • Size • Complexity • Similarity • Suppression of assemblies with AM process • Necessity of post processing after print • Material • Compliment of specific geometric condions for AM (risk of residual stresses) • Weight • Material consumption • Processing time (AM vs traditional manufacturing methods)

Fig. 3. Factors for selection of parts to be manufactured by AM

4.2 Methodologies used for part selection for AM

Figure 4 summarizes some of the methodologies used for part selection for AM [9,10,11]. The methodologies used for part selection for AM can be categorized into two classes: bottom-up and top-down approaches. In the bottom-up approach [10] the selection process relies on the inputs from AM expert assessments conducted in workshop mode. Some attempts have been done by Knofius et al. [11] to develop a top-bottom approach for part selection, but this approach is still in its infancy and further research will be needed.

Frandsen et al., 2019		Knofius et al., 2016	Lindemann et al., 2015
Multi-criteria decision support tools	<ul style="list-style-type: none"> • Pairwise comparison • Distance-based method • Outranking • Compromise ranking • Weighted linear optimization • Rule-based decision making 	<p>Top-down approach</p> <p><u>Assesment #1 - Go/No-Go attributes</u> Does the spare part complies with technological constraints that are enforced by the current advancement of AM technology?</p> <p><u>Assesment #2</u> Definition of weight factors for different spare parts attributes according to the preference of the company to print specific spare parts</p> <p><u>Assesment #3</u> Calculation of weighted average scores for each spare part and selection of highly ranked spare parts based on their scores</p>	<p>Workshop-based bottom-up approach</p> <p><u>Step 1. Information phase</u> The AM technology is introduced to the AM end-udser to help them to select a large number of sample parts without further help of AM experts</p> <p><u>Step 2. Assessment phase</u> AM experts rank the parts using a trade-off methodology matrix (TOM)</p> <p><u>Step 3. Decision phase</u> AM experts together with end-user finalize the part(s) that represent the biggest benefit to be redesigned and manufactured by AM (economic aspects)</p>
Bi-criteria analysis			

Fig. 4. Methodologies used for selection of parts to be manufactured by AM

5 Why is part selection for FIM different from part selection for AM?

5.1 Factors to be considered for part selection for FIM

The technical and economic factors needed for part selection for FIM are not identical to the factors used for part selection for AM. As the factors which impact output quality of different AM processes are well-understood, the part selection methodology for AM does not explicitly need to consider which factors impact quality and to what extent. As FIM is a recently developed technology, part selection for FIM must ensure that the parts produced using FIM meet the desired quality.

The design rules for direct printing of parts using DLP have been developed by research groups [12]. The existing design rules are applicable for direct printing of “positives” and not necessarily for indirect printing of “cavities”. Therefore, in order to investigate which factors, have the highest impact on the FIM parts and to what extent they interact with each other to generate the desirable quality of the parts, we need to conduct Design of Experiment (DOE) to determine the optimal feasible range of the parameters. DOE will be followed by validation of DOE results to finetune the ranges of the parameters (printing and injection molding) which give the highest quality FIM parts. Beside this, there are some FIM-specific technical parameters such as aspect ratio, thickness ratio etc. that need to be considered during the part identification process for FIM. In addition to the technical differences between FIM and AM, the economic parameters for part selection for FIM is not identical to part selection for AM.

5.2 Proposed methodology for part selection for FIM

Due to the difference between the factors for part selection for AM and FIM and the uniqueness of the FIM process, there is a need for developing a new methodology for part selection for FIM. In this study, we propose a hybrid approach, which combines the empirical methods with experimentation (Fig. 5). It should be noticed that the sequence of the screening and filtering steps in our approach differ from those suggested in academic literature [9,10,11]. Prior literature on part selection for AM usually stop once the parts are scored and ranked. Such an approach is suitable if we can assume that product quality requirements are met. But in reality, parts selected for AM may not meet quality requirements as quality requirements are explicitly not considered in the part selection model. As FIM is a newly developed technology, we want to understand the role of the different parameters, which influence the quality of the parts. Hence, we will conduct experiments to determine the most optimal ranges of the parameters.

Our proposed method starts by inputting some reference/representative CAD files suitable for FIM based on experience of the innovator company, which developed and commercialized FIM, into one of the commercial part identification tools. Once the most similar components from the end-user part library/PLM were identified, the parts will be filtered based on the critical dimensions for FIM (in this case, we have chosen 5cmx5cmx5cm to facilitate size filtration). This filtering will be followed by cluster analysis to group the identified parts based on important factors for FIM part selection

such as aspect and thickness ratio. As the clusters can be quite different and the factors involved are interdependent, we need to apply some decision rules using Fuzzy Interference System (FIS) to rank the parts within each cluster using user-defined technical and economic criteria. At this stage, we should have a set of parts potentially manufacturable by FIM. If substantial number of parts are identified at this stage of the process, a preliminary screening based on lifecycle cost will be conducted. Lifecycle cost is the cost of raw materials, production (man hours, machine hours, energy etc.), inventory and transportation costs over the lifecycle of the usage of the part.

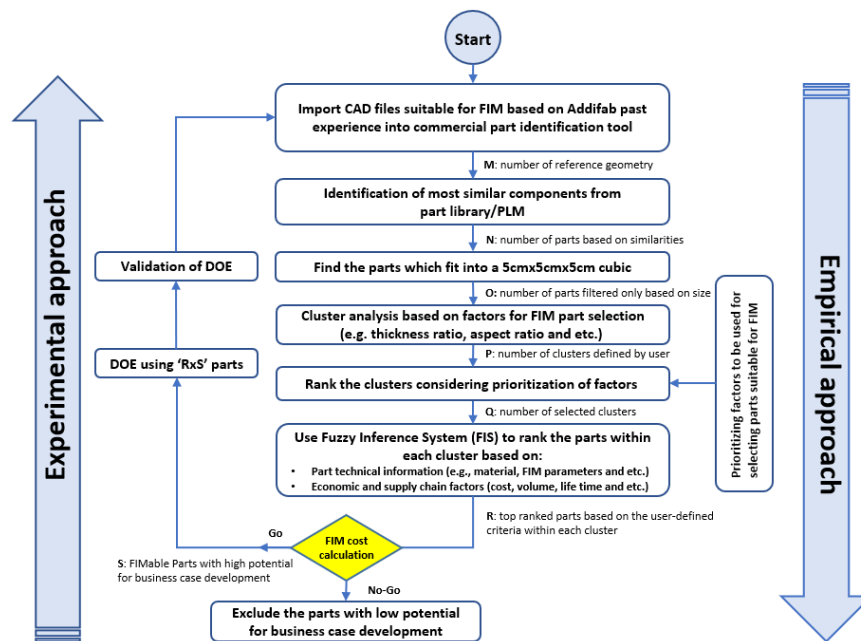


Fig. 5. Proposed hybrid methodology for part selection for FIM

After the above-mentioned process steps are conducted, we will be ready to start the experimentation part of our approach, in which we will produce and evaluate a number of the components identified. The reason behind the experimentation is that we lack knowledge about which factors are most important and how they interact with each other to generate the desirable quality of the FIM parts. To address this lack of knowledge, we need to conduct a Design of Experiment (DOE) followed by validation of the DOE results to finetune the ranges of the parameters which gives the best results. Finally, the optimum feasible range of FIM parameters will be used to develop a predictive model to analytically find the new FIMable parts without repeating the algorithm for the new parts.

6 Conclusion and discussion

The existing literature on part selection for AM cannot be used to evaluate indirect FIM printing where the objective is to print a mold insert with an inner cavity. Therefore, development of a part screening tool for FIM is perceived as essential. This research bridges the gap and provides a framework for part selection for FIM. The proposed generic framework will be suitable for any new hybrid manufacturing technology which combines AM with conventional manufacturing as for such technologies, the critical factors and the relationships between them will be identified while selecting parts which can be produced with desired quality by those technologies.

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