The implication of rapid technologies on the design process

by

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ABSTRACT

This dissertation focuses on the challenges of design and additive manufacturing (AM). It considers the challenges that such a freeform manufacturing process can have on design freedom. Much of the current literature is focused on this design freedom only as a positive, and work to improve design-for-AM, and how to better exploit the technology. On the contrary, this work looks at how that design freedom can be a challenge if and when a move from AM to a more conventional process is needed. The work is broken into three studies related to the implication of rapid technologies on the design process. Firstly, a user study to examine the effect of AM on design fixation was implemented using two groups, a Design for Conventional Manufacturing (DFCM) group and a Design for Additive Manufacturing group (DFAM). It was found that designers who trained on AM knowledge (DFAM group) experienced a design fixation on non-producible features and produced harder to conventionally manufacture designs, even when asked to modify designs for conventional manufacturing. This brings to light the negative effect of AM knowledge on designers and necessitates treatment methods. Therefore, the second part of this work focused on treating the negative effects of AM knowledge on designer skills. Mainly, a user study investigated the use of Design for Manufacturing (DFM)-based software in mitigating design fixation on non-producible features. The 3D feedback of the DFM software helped to reduce design fixation on non-producible features and improved the machinability of modified designs. The DFM feedback helped designers by highlighting areas in the design that could have machinability problems, however, it did not provide designers with a suggestion on how to modify and migrate their designs from AM to Conventional processes. Thus, the third part of this dissertation proposed a method that can provide a designer with suggestions to modify a design and allow its migration from AM to conventional processes. The method determines best cut lines for dissecting a design into pieces such that the surfaces of problematic features become more machinable. The method was tested, and results showed that the method can dissect a design into components that have better machinability on average than the original design. Overall, this work suggests the use DFM software and a dissection method for treating the design fixation related to AM and for facilitating the migration of designs from additive to conventional manufacturing. This work could be applied to manufacturing industries, particularly for AM parts that are slated for mass production which will require migration to conventional methods.

GENERAL INTRODUCTION

Background

As is true with art, engineering design is a mean by which thoughts, experiences and feelings are expressed and conveyed. However, unlike non-utilitarian artifacts, the ideas and thoughts in engineering design processes are usually visualized, developed and built to fulfill market needs (Shah, Smith & Vargas-Hernandez, 2003). With respect to the engineering design process, it can be outlined in six steps; 1) need identification, 2) problem definition, 3) information gathering, 4) conceptualization (ideation), 5) evaluation (detailed design and testing) and 6) communication of design (Dieter, Schmidt & Azarm, 2009). Designers usually follow these steps while designing, however, the workability or success of developed designs cannot be guaranteed. Generally speaking, the failure of a design can be linked to its poor functionality, low quality, high cost, late time to market, or non-stability of demand caused by product success (Anderson, 2014). These reasons of failure are usually considered as manufacturability issues that were not considered/resolved during the design process. Therefore, different methods such as Design for Manufacturability (DFM) are used to increase efficiency of the design process in creating successful and cost-effective designs. DFM is an approach that enables the designer to consider manufacturing capabilities early during the design process to ensure easy and economic manufacturing (Sreekumar, 2013; Boothroyd, Dewhurst & Knight, 2010; Al-Dwairi, 2008). DFM enables designers to minimize manufacturing complexity through use of common processes, materials, and parts, minimizing part and process counts, and simplifying shapes and finishing requirements. With the aid of DFM, designs can be produced on time with lower cost while maintaining quality (Boothroyd, Dewhurst & Knight, 2010; Al-Dwairi, 2008).

In the past 20 years, the use of DFM and the design process in general were further facilitated with the introduction of Rapid Prototyping technologies (Campos, Mungula & Lloveras, 2007; Broek, Sleijffers, Horváth & Lennings, 2000; Diegel, Xu & Potgieter, 2006). Rapid prototyping(RP) technologies is a term used to describe processes that enable the production of physical models automatically from 3D computer model for function, form and fit testing of new designs (Noorani, 2006). Other terms such as solid free form fabrication, additive manufacturing (AM) and 3D printing are used interchangeably with Rapid Prototyping (Petrovic et al., 2011). Generally, AM uses layer-based manufacturing to build 3D objects, wherein the 3D CAD model is sliced into 2.5D layers that are printed one by one in a bottom-up approach (Gibson et al., 2010; Petrovic et al., 2011). A generic illustration of a layer-based process is shown in Figure 1. The layer-based approach allows complex features and fixture creation automatically, overcoming visibility and process planning problems and consequently eliminates the need for 4-5 axis machines or skilled labor (Frank, Peters, Luo, Meng & Petrzelka, 2009; Mansour & Hague, 2003).

Many additive manufacturing methodologies have emerged over the past few decades. Some of the most notable methods are Stereolithography (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Laminated Object Manufacturing (LOM), and 3-D Printing (Hague, Mansour & Saleh, 2003; Noorani, 2006). These methods vary in terms of type and form of materials used to print layers, energy sources and/or the general means by which the printed layers are created and bound for building physical models (Gibson et al., 2010; Petrovic et al., 2011).

Additive manufacturing has been spread widely because of its capability of producing parts directly from CAD models without tooling, using little machining setups and human intervention and with materials waste 40% less than conventional processes (Gibson et al., 2010; Petrovic et al., 2011). Being a tool-less process enables the production of customized parts with nearly unlimited geometrical complexity. More, recent research illustrates how AM can use multiple materials to build 3D objects (Mansour & Hague, 2003).

However, these methods have limitations on part accuracy, surface finish, size, durability and materials (Petrovic et al., 2011). Additionally, these methods are characterized by their small production quantities, high equipment cost and long processing times (Frank, Joshi & Wysk, 2002).

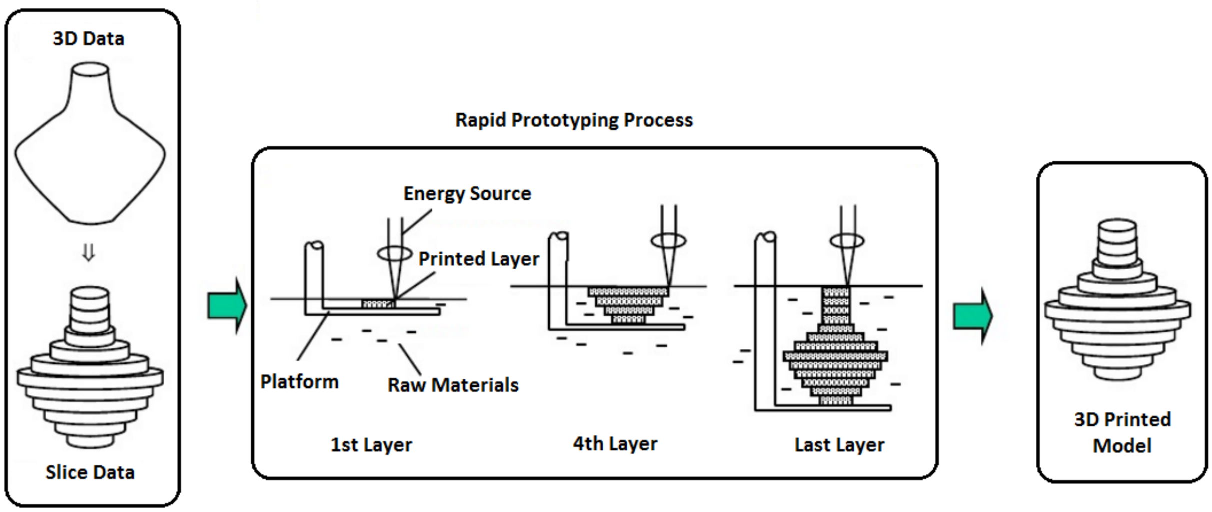

Fig.1 Principle of Layer based manufacturing

The capabilities of AM processes make them suitable for early design visualization, some functional testing and design refinement of new concepts; in general, a very strong design support tool. The advantages of using AM as a design support tool appears in shortening product development time, reducing cost, leading to better customer satisfaction (Gibson, 2005; Mansour & Hague, 2003). These technologies were kept from being used for the production of functional parts because of their limitations on materials, part accuracy, size and durability (Noorani, 2006). However, the advancement of these technologies has led to actual use of AM parts, especially in highly customized consumer products.

In addition, AM parts are often married to a secondary operation, like CNC machining for finishing. Some research has also considered making purely subtractive processes, more akin to rapid technologies, with higher degrees of automation (Frank et al., 2002; 2004; 2009). Hybrid AM processes take the benefits of layered manufacturing and conventional CNC machining processes to solve the problems associated with traditional AM and machining process individually (Frank et al., 2009). As in traditional AM, hybrid AM is able to fabricate parts, layer by layer with negligible human intervention but then takes advantage of CNC machining to fabricate functional parts with high accuracy on machined surfaces. These capabilities of hybrid AM make it a good candidate to substitute the conventional machining process for rapid manufacturing of functional parts.

Purely subtractive-based RP uses CNC machining as a rapid manufacturing process to rapidly and automatically process plan and create functional parts using appropriate materials. These processes benefit similarly from a layer-based approach to generate process, fixture and setup plans quickly to machine complex shapes with high accuracy. Being a purely subtractive process, the produced parts are free of weak interlaminar strength problem that is usually common in AM. However, the long processing time remains the main problem with these processes, but still better than conventional CNC machining in case of highly customized and complex designs (Frank et al., 2002; Frank et al., 2004).

In summary, the early use of RP/AM was as a design support tool to facilitate and accelerate product development processes. On the other hand, the current trend to use AM as a manufacturing process for new products, could cause designers to ignore design complexity as being problematic (Mansour & Hague, 2003). For example, Mansour (2003) discussed the advantages of using AM in freeing designers from considering design-for-injection-molding guidelines. For a part to be injection molded, designers should minimize complex features and geometries such as undercuts, blind holes, avoid sharp corners, minimize weld lines, sink, ejection, and gate marks, and to use draft angles and consistent wall thicknesses. These guidelines usually resolve issues related to tooling and dies of injection molding. In contrast, AM is a tool-less process, therefore, designers do not need to consider these guidelines, as illustrated in Fig.2.

Fig.2 Bracket, designed for a conventional process (left), designed for AM(right). https://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study

However, these new functional and complex parts, manufactured with AM, are typically only suitable for short production runs (Frank et al., 2009). In addition to some material and finish problems, the AM process is generally slow and hard to scale up cost effectively. Therefore, thinking of these new functional parts for mass production, when accepted in the market, brings need again for redesign of these new products for ease of manufacturing.

The contradictory manufacturing capabilities of AM and other conventional production processes, questions whether designing parts for AM, at early stages of its introduction in the market, may impair a designer's ability to redesign it for ease of manufacturing later for mass production. In other words, the designer may experience a difficulty in redesigning parts for ease of manufacturing due to the complex nature of parts designed for AM; designers became fixated on their initial designs. The notion of difficulty in redesigning an AM produced part for ease of manufacturing can be supported by recent European and aerospace company's practices, where they started to rely heavily on AM to protect their designs and ideas from unauthorized duplication through mass production (Petrovic et al., 2011; Hillis, 2015).

Motivation

Designers are generally under pressure to quickly respond to market needs for introducing new products, therefore, there is a need to shorten the design process. Additive manufacturing processes are believed to help in accelerating product development and shorten time to market. The success of AM technologies in creating complex and functional parts directly from CAD models encourages use of them as a manufacturing process. However, long processing times, issues with weak interlaminar strength, dimensional control and finish problems limits their application for small production volumes.

The limitations of AM as manufacturing process materialize if demand for the new product increase to a degree that requires mass production. Therefore, a redesign of the successful product for ease of manufacturing using one of the traditional manufacturing capabilities is required. However, the complex nature of AM produced parts combined with time constraint are believed to complicate the redesigning challenge, causing the designer to fixate on their AM designs. Design fixation on initial designs for AM are not desirable because it is expected to result in more redesign iterations before a part is readied for mass production. The problem becomes more serious in the case where a design simply cannot be made feasible with conventional methods, where huge losses will be incurred. Therefore, there is a strong motivation to investigate the negative effect of AM as a manufacturing process on a designers' abilities to redesign parts for conventional manufacturing processes. Additionally, we are motivated to investigate new methods for treatment of fixation, and to ease migration of designs from AM to conventional processes.

Objectives

This research focuses on three areas including, 1) rapid technologies impact on designer skills, 2) treatment method of the negative effects of AM on designer skills and 3) methods to facilitate migration of a design from AM to conventional processes.

The first objective of this research focuses on designing, testing and conducting a user study to investigate the effect of additive manufacturing on designer's skill. The positive effect of rapid technologies on designer skills were assessed, however, the key goal was to prove negative effects of rapid technologies on Design for Manufacturability skills.

The second objective is to design, test and conduct a user study to investigate the effectiveness of using DFM based software in mitigating design fixation on negative manufacturing features. The DFM based software is suggested to treat the negative effects caused by AM on skills, mainly, design fixation.

The third objective of this research focuses on developing a method to facilitate migration of designs from rapid technologies to conventional manufacturing processes.

Thesis Organization

This dissertation is organized as follows: a general introduction is presented in Chapter 1, followed by a detailed review of literature related to design for manufacturing, effect of RP/AM on the design process and design fixation in Chapter 2. A study on the effect of rapid technologies on designer skills is presented in a journal paper format in Chapter 3. Chapter 4 presents a study of DFM-based feedback to mitigate design fixation. A method to facilitate migration of designs from rapid technologies to conventional manufacturing processes will be presented in Chapter 5.

The final chapter will provide general conclusions and future research directions of the presented work.

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RELATED WORK

Design for Manufacturing

The design phase is highly crucial due to the nature of decisions involved that account for more than 70% of part life cycle cost. Therefore, greater efforts are usually spent at this early stage to avoid problems and higher cost at downstream activities (Chuan & Okudan, 2010; Ullman, 2010). During this stage, different design practices and guidelines such as design for manufacturability, assembly and others are used to ensure efficiency in creating successful and cost-effective designs (Chuan & Okudan, 2010).

Design for manufacturing (DFM), also called *design for manufacturability*, is a term used to describe practices to design parts for ease and economic manufacturing using conventional production processes (Robert, 2015). With DFM, the design phase is integrated with process planning of the part, where design decisions for the part will be taken while considering available manufacturing capabilities (Robert, 2015; Boothroyd, 2010 & Al-Dwairi, 2008). The ease of manufacturing and cost savings are typically achieved through a set of DFM design principles or guidelines. These principles focus on simplicity, material and component standardization, design modularization, use of liberal tolerances, and use of easily processed materials. DFM guidelines also focus on collaborating/consulting with manufacturing personnel, minimizing secondary processes, design for expected production volume, utilizing special process and materials characteristics, and avoiding process restrictiveness. For example, if a designer exploited the simplicity principle, they will tend to minimize parts count, use less intricate shapes, loosen tolerances and reduce the number of manufacturing operations. The use of liberal tolerance principle implies that designer will try to avoid tight tolerances in the design. Tight tolerances are not desirable because they require extra processes, higher tooling costs, longer production cycles, more material waste and rework cost, higher skilled labor, and more stringent material quality. In other words, DFM principles aim to satisfy the quality of part's design while shortening its development cycle time and decreasing its cost (Boothroyd, 2010; Al-Dwairi, 2008 & Wood, 1999).

Depending on manufacturing process, different variations of DFM focusing on particular process capabilities and limitations exist, such as design for machining or design for injection molding. Generally, for a part to be easily machinable, a designer should avoid features that will create tool accessibility and visibility problems and consequently lead to more machining setups, time and cost. In other words, designer should avoid deep radii and sharp internal corners, undercuts, narrow and deep depressions, enclosed and captured cavities, thin wall sections and/or extremely long sections. Further, the design for machining rules provide some tips to improve machinability of part such as selecting standard materials, standard pre-shaped workpieces, use of standard and simple shape machined features to maximizing symmetry of part design (Boothroyd, 2010; Al-Dwairi, 2008).

Overall, considering DFM guidelines and rules helps to create a more efficient, robust, and cost-effective part design and production method. However, it is not always the case, there will always be exceptions where doing something different than guidelines may lead to a better or as good as guidelines results (Boothroyd, 2010). Due to many restrictions involved, it is claimed that DFM can limit design creativity and fails to provide redesign suggestions to alter shapes when the design is unacceptable (Xie, 2003). These DFM shortcomings can be handled, at least in the short term, with advent of rapid prototyping (RP) technologies like Additive Manufacturing, as will be discussed in the next section.

Rapid Prototyping and Design process

In the literature, few studies discussed the impact of additive manufacturing /prototyping on the design process. The discussions have focused on the advantages of AM in providing more design freedom in term of geometrical complexity, materials choice, in addition to opportunities for mass customization (Campbell et al., 2012; Hague, Campbell & Dickens, 2003; Hague, Mansour& Saleh, 2003; Mansour& Hague, 2003; Thompson et al., 2016; Eyers & Dotchev , 2010 & Bernard & Fischer, 2002). The AM approach is able to produces parts with nearly unlimited geometrical complexity at no extra cost; known as geometry for "free". That is, the process is typical the same cost per volume whether it is simple or complex; the price is still relatively high. Cost saving can be rooted from fact of being a tool-less technology, where customized and complex parts and associated sacrificial supports are built simultaneously layer by layer. Additionally, the characteristic of AM wasting less material compared to other manufacturing processes can further reduce cost. Additionally, AM was found to positively benefit the design process by enabling gradient and mixes of different materials to produce design feature with extra functionality. In other words, different materials combination can be deposited gradually in particular locations while building part to provide a certain properties or function (Campbell et al., 2012; Hague, Campbell & Dickens, 2003; Hague, Mansour& Saleh, 2003; Mansour& Hague, 2003; Thompson et al., 2016).

The implication of AM on the designer's work were also discussed. Generally speaking, it was stated that AM encourages designers to ignore traditional design practices such as DFM, providing more design freedom. With AM, a designer has the freedom to be more imaginative and to create highly complex designs that were implausible (Campbell et al., 2012; Hague, Campbell & Dickens, 2003; Hague, Mansour& Saleh, 2003; Mansour& Hague, 2003; Thompson et al., 2016).

For example, for a part to be easily moldable, it is usually required to have draft, uniform wall thickness, no reentrant geometry and several other geometrical restrictions. However, with the fact that AM does not require tooling or a mold to produce part, the geometrical restrictions generally no longer exist (Hague, Mansour & Saleh, 2003; Mansour & Hague, 2003).

All these together can justify the opportunities AM provides for mass customization, where customized parts are produced at reasonable and /or same cost compared to their standardized counterparts. In other words, AM facilitates production of cost effective custom parts/products (Hague, Campbell & Dickens, 2003; Eyers & Dotchev, 2010; & Bernard & Fischer, 2002). AM facilitates mass customization by incorporating the customer in the design process as a designer or as collaborator within the design team (Hague, Campbell & Dickens, 2003). With AM, the users can design their own product through selection from restricted predetermined alternatives or by using a user friendly innovate interface, or partnership with designers over the internet. Once they design their parts, users can then produce their parts using their home-based AM system or online with the aid of a service bureau. A simple example of mass customization wherein huge time and cost saving can be seen clearly founds is in the jewelry field (Bernard & Fischer, 2002). To manufacture jewelry such as a gold ring, companies may either rely on goldsmith craftsmen using lost wax casting or may use conventional process which include stamping, micro fusion and electroforming processes. Depending on the complexity of the ring design, workers may take as short as 4 days or as long as 3 months to deliver a ring to the customer. In contrast, custom made ring models can be produced using AM within 5-10 hours.

Although considerable literature provides examples like the jewelry making process above, the *negative* impact of AM on the design process is largely not discussed in literature. One possible negative impact is that ignoring DFM will became problematic if the demand for the part rises suddenly for some particular non-custom part made for AM. In this scenario, a redesign of that part for mass production is required. In some cases, the designer will face difficulty in redesigning their part for ease of manufacturing because of being fixated on their initial ideas intended for AM; a problem called Design Fixation.

Design Fixation

Fixation was initially mentioned as being a type of a psychological inertia that impedes personal creativity and problem-solving ability, resulting from cognitive adherence and/ or bias to preexisting knowledge (James, 1998; Crilly, 2015). Over time, the term ”fixation” was used by researchers in the design area to describe a cognitive barrier that causes blind adherence of designers to a set of solutions, limiting design creativity and innovation (Jansson & Smith, 1991). These cognitive difficulties were known as design fixation. Later, the definition of design fixation was narrowed to the overreliance of designers on the features of preexisting designs leading to designs similar to previous ones(Youmans & Arciszewski, 2014).

In psychology, fixation was related to functional fixedness(Purcell & Gero, 1996), or the *Einstellung* effect (Bilalić et al., 2016; Purcell & Gero, 1996) or the *counter sunk* effect (Viswanathan & Linsey, 2013). Different classifications were used to categorize fixation (Purcell & Gero, 1996; Youmans & Arciszewski, 2014). In Youmans’ classification, fixation can occur unconsciously, consciously or intentionally. The unconscious fixation was believed to be related to *Einstellung* effect, i.e., blind adherence to the influence of prior designs (Bilalić et al., 2016). Conscious fixation was linked to functional fixedness where designers experience difficulty in finding new use or function for existing objects or features to solve problem(Purcell & Gero, 1996). Intentional resistance was related to the counter sunk effect where least resistance path is preferred to generate solutions(Viswanathan & Linsey, 2013). The preference of least resistance path was justified by inefficiency of investing time and effort on a new solution if there is already a good one (Crilly, 2015); limiting creativity.

Being considered as a cognitive bias/phenomenon, the mechanism through which fixation occurs was extensively discussed in field of cognitive psychology. Psychologists suggested that fixation can result from interaction between working memory and associative long term memory (Youmans, 2011). Many researchers stated that recently activated knowledge directs thinking to a known solution set during creative reasoning/task, thus causing fixation (Agogué, 2014; Jansson & Smith, 1991; Moreno, Yang, Hernández, Linsey & Wood, 2015; Youmans, 2011). According to cognitive studies, this bias can be explained by part set cuing phenomena in memory where the distraction effect of memories associated with activated knowledge inhibit retrieval/ rehearsal of other inactivated memory(Bilalić et al., 2016).

One of the leading studies that tried to interpret the mechanism through which fixation occur was (Agogué et al., 2014). They proposed a theoretical framework based on a Concept -Knowledge (C-K) design theory to model design fixation. They stated that fixation can be characterized by a set of restrictive heuristics that only use the spontaneous activated knowledge in knowledge space and map it to restrictive partition in the concept space, narrowing down exploration of the solution space and limiting/inhibiting creativity (Fig. 3). According to (Agogué, 2014), restrictive partition in the C space represents the possible solutions that spontaneously came to mind while thinking of design problems. It was stated that fixation can be mitigated by inhibiting spontaneous solutions (i.e. restrictive partition in C-space) to support expansion of solution space and consequently development of expansive heuristics; exploring solutions outside restrictive C-space.

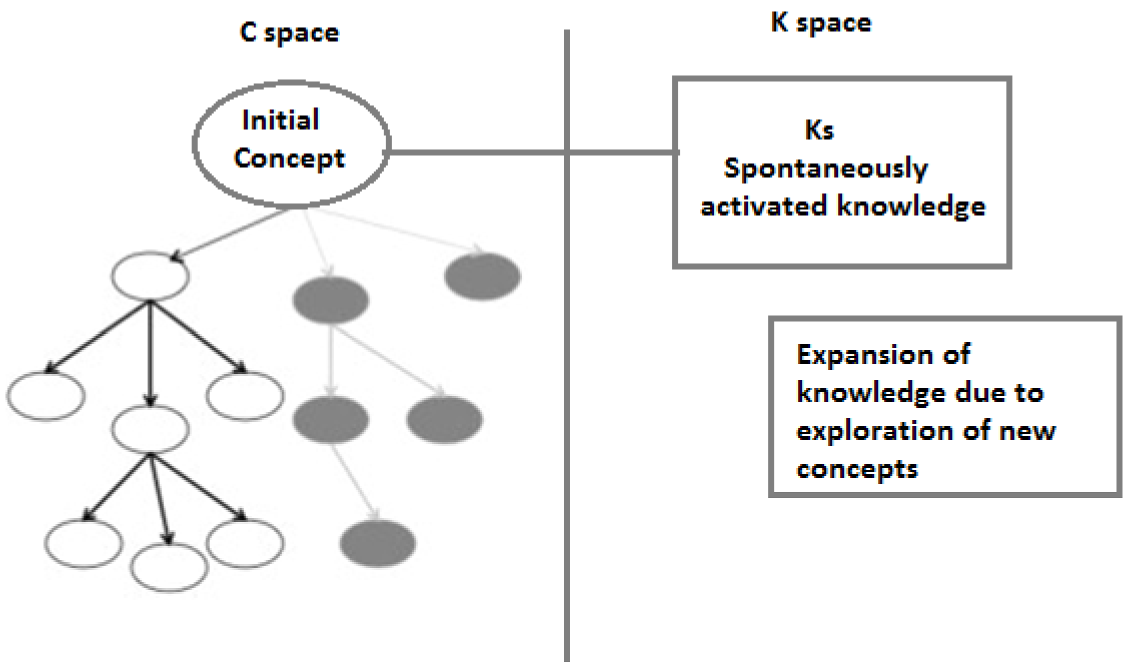

Fig. 3 Model of a fixation effect by Agogué (2014) : spontaneously activated knowledge (Ks) will determine partitions in the C space (white) and lead to a reduced exploration of possible solutions (grey concepts will not be explored)

Factors that encourage fixation

Design and engineering studies in line with cognitive studies showed that design fixation can be encouraged by many factors. Qualitative studies discussed that the fixation could be triggered by either organizational and /or precedential factors. These factors lead to fixation on the problem, process, or solution. The organizational factors represented by project time/cost constraints, and blame culture were found to cause process fixation. Narrowing the exploration space of ideas will need immediate action to avoid delays in project completion or excessive cost. Also, being in a work environment that is intolerable to failure made designers reluctant to change from either prior good or reliable solution paths (Crilly, 2015) .

The precedential factors, mainly in the form of exposure to prior art and bias to initial solutions cause fixation on the solution, whereas client briefing causes fixation on the problem(Crilly, 2015). The effect of prior art and designer commitment to initial solutions on fixation were the focus of experimental studies (Agogué, 2014; Bilalić et al., 2016; Cheng, Mugge, & Schoormans, 2014; Jansson & Smith, 1991; Purcell & Gero, 1996; Viswanathan & Linsey, 2013; Youmans, 2011) . In contrast, the client briefing was slightly discussed in qualitative studies only. The client briefing was defined as client setting on particular ideas, mainly, prior solutions or initial solution presented by designer. The client adherence to prior or initial ideas was believed to complicate the designer job of detaching from these ideas because emotional nature of client that made them resist alternative ideas (Crilly, 2015 & Robertson, 2009).

Experimental studies examined the precedential causes of fixation, wherein, researchers suggested that fixation can be encouraged by precedential factors that can be either intrinsic and/or extrinsic to designers. The discussions of intrinsic causes included mainly designers 'expertise' (Linsey et al., 2010), or familiarity of domain knowledge (Purcell & Greo, 1996; Cross, 2004), age (Agogué, 2014), personality traits (Toh et al., 2012), and standardization of design methods/process (Crilly, 2015).

Studies showed that the role of designer expertise in creating fixation was linked mainly to their experience of failure and their interaction with a variety of prior solutions (Crilly, 2015; Viswanathan & Linsey, 2013). The designer's experience of failure made them reluctant to change preexisting reliable solution paths, or a particular solution (Crilly, 2015). Their interaction and experience with a variety of preexisting possible solutions is another dimension of designer expertise that was found to cause fixation, where more experience and interaction with prior solutions led to a higher probability of producing similar solutions. However, it might be argued that the experience of variety discourages fixation because of a designers' awareness of available solutions, hence they will manage to avoid fixation. This argument was supported by some researchers, where they found that the high level of expertise hinder fixation compared to lower expertise level (Bilalić et al., 2008a; Viswanathan & Linsey, 2013; Dror ,2011).

The impact of domain knowledge and discipline on fixation were studied by (Purcell & Gero, 1996). In their study, two groups of mechanical engineers and industrial designers were employed to replicate an experiment used by (Jansson & Smith, 1991) which included a mechanical design problem. They found that fixation is more likely to occur when the principles embodied in the design problem match the knowledge base of the designer; industrial designers were found to be less susceptible to fixation and more innovative compared to mechanical engineers. These findings were supported by (Dahl & Moreau, 2002; Marsh et al., 1996), where they addressed that the more familiarity of domain knowledge with the design problem and /or example, the lower originality of the design, hence a higher degree of fixation. However, it was argued that the lack of familiarity of domain knowledge may encourage fixation because the designer will tend to over rely on available resources, resulting in solutions similar to existing.

Individual differences in term of age and its effects on fixation were slightly discussed by (Agogué, 2014), where it is has been observed that older individuals tend to fixate more than younger ones especially when dealing with life experience problems . However, individual characteristics such as age can be confounded by other factors such as experience and educational attainment.

Over time, design methods became well developed and standardized given available technological/organizational capabilities. The standardization of the design methods encourages designers to resist deviation from exiting reliable methods, that is, became cognitively path dependent. The driving force for this phenomenon was related to less design effort and time in addition to minimizing risk of failure. However, path dependency while designing constrains the exploration space and therefore increases risk of fixation.

The extrinsic factors studies relied on exposing subjects to external stimulus (i.e. preexisting solutions) verbally or pictorially (Jansson & Smith,1991) or physically (Youmans, 2011) using different levels of abstraction of stimulus(Cheng, 2014) at different point of time (Youmans, 2011; Tseng, 2008; Dow, 2011). Many studies showed that pictorial examples (i.e. sketches or images) cause more fixation than verbal description and that the richer the pictorial stimulus is the more fixation is expected. (Cheng et al., 2014) found that designers who worked with full images of precedents produced less original designs compared to those who worked with partial images. Some studies presented pictorial stimulus in physical form to induce fixation(Moreno et al., 2015; Youmans, 2011). In these studies, participants were asked to either build a physical model of preexisting solutions using a given construction set prior to generation of their ideas or to use physical models while generating ideas. The effect of these physical models on fixation were found to be dependent on prototyping design approach. Dow (2011) found that serial prototyping constrains designer ideas to be a variation of their initial ideas, unlike parallel prototyping approaches where more diverse and better designs were obtained.

The effect of feedback timing during the design process were also found to affect fixation. As in the prototyping approach, serial feedback was found to induce more fixation than parallel feedback. In serial design processes, the designer tends to anchor on their initial ideas and use feedback to refine these initial ideas. In contrast, parallel process designers had more time to explore and use feedback at the end of the design process to contrast between ideas (Dow, 2011).

Additionally, the level of realism of design environment was considered as an external factor that constrains designer thinking. The partial design environment and conditions plays an important role in increasing the risk of fixation compared to a full design environment that involved use of physical prototyping. Designers in a partial design environment will usually experience higher working memory load compared to those in a full environment. Where instead of fluctuating tasks between thinking, reasoning and interaction with the physical model, they limited their activities to mental actions, and consequently, failure of detecting fixation features. However, the effect of partial design environments can be moderated by teamwork instead of individual work as it will be discussed later in the defixation factors section (Youmans, 2011).

Factors that discourage fixation

In literature, the factors that discourage fixation were discussed inherently within approaches or methods used to mitigate fixation. Generally speaking, fixation can be discouraged through teamwork (Linsey, 2010) and facilitation (Crilly, 2015) model making/physical prototyping (Youman, 2011), client expectation and use of systematic design methods, both intuitive and logical (Crilly, 2015; Wood, 1999). The vast majority of studies stated that groups generally create more original and diverse designs than single individuals because of assembly bonus effect. The role of teamwork in alleviating fixation was related to diverse perspectives brought to design the process as a result of different backgrounds, experiences of the designers (Crilly, 2015; Dow, 2011), reduction of individual mental/cognitive workload due to task subdividing (Youmans, 2011; Youmans, 2006) , in addition to the feedback of the team while designing (Crilly, 2015). However , it was argued that teamwork can cause fixation because of the *social loafing effect* (Gallupe et al.,1991) ,and poor communication that hinders potential advantages of team work (Crilly, 2015; Dow, 2011; Youmans, 2011) .In other words, the benefit of teamwork in mitigating fixation can be seen only when there is an effective team communication and collaboration (

Youmans, 2006) and/or in partial design environments where there is no physical interaction (Youman, 2011).

Another factor that discourages fixation is the use of physical models during design process. (Youman, 2011, Crilly, 2015) described that making or interacting with physical models while designing reduces mental workload (cognitive demand) ,and consequently provides more resources(i.e. attentional and time resources) to explore new ideas and to detect and eliminate fixation .Crilly (2015) and Purcell and Greo (1996) stated that making models provides an immediate feedback to critique, evaluate, detect, and subsequently eases detachment from unacceptable (negative), initial, or redundant ideas. However, it was argued that the timing of interaction with physical models affects the extent to which fixation can be mitigated. Christensen & Schunn (2007) illustrated that participants fixated more when they were allowed to interact with the physical model before idea generation, whereas (Youmans, 2011) stated that those who were allowed to interact with physical models while designing fixated less. Therefore, it can be stated that interacting with physical models should be all the way before and during the design process to effectively reduce fixation. The interaction with these models during the whole process will act as a continuous reminder of preexisting solutions, consequently facilitate detection and eliminating of fixated features and hence strengthening editing process of existing and initial ideas.

The role of client behavior on fixation was found to have two different dimensions. As discussed before, clients can act as a sources of fixation when they are set on a prior solution (Crilly, 2015) . On other hand, the assumption that the nature of a customer being eager for unusual, variety and exceptional ideas motivates designer to explore new designs to exceed customer expectation, and hence reduction of fixation.

The effect of design methods on reducing design fixation were slightly discussed in literature. (Grilly, 2015) stated that the use of systematic design methods, whether it included intuitive or logical idea generation methods, can help in treating fixation. For example, the use of germinal type intuitive methods, such as morphological analysis and brainstorming help in breaking mental blocks. Whereas, logical idea generation methods help to systematically decompose and analyze design problems and generate solutions based on the use of science and engineering principles and /or past solutions' data bases and catalogues such as TRIZ and SIT. In other words , the logical methods are believed to facilitate thinking outside-the-box and bridging of different domains and disciplines to bring new perspectives to the design process (Shah, 2003; Youmans & Arciszewski, 2014).

Finally, it is mentioned that designer experience, in particular experience of failure, helps in reducing fixation. Viswanathan & Linsey (2013) found that experts experience less fixation compared to novices because of their better abilities for retrieval of relevant information and concepts mapping from disparate domains due to wider knowledge and experience in addition to their better problem framing abilities.

Fixation mitigation methods

Some studies tried to categorize treatment methods based on the source of fixation and implementation method (Moreno, 2014). Broadly speaking, fixation caused by extrinsic factors were treated by providing de-fixation instructions (Christensen, 2007; Chrysikou & Weisberg, 2005), or through the use of defixation materials in the form of abstract problem formulation (Zahner & Nickerson, 2010), use of partial pictorial stimulus (Cheng, 2014), verbal analogy (Linsey, 2010; Viswanathan, 2013) or visual analogy (Casakin & Goldschmidt, 1999). Other researchers relied on having designers work in full design environments to mitigate fixation by means of incorporating physical prototyping during the conceptualization phase(Youman, 2011), or through product dissection (Grantham et al., 2010) .Other methods such as the use of intuitive idea generation methods (Youman, 2014; Crilly, 2015), computer-assisted design (Dong & Sarkar, 2011), cognitive information feedback systems (Youman, 2005), interdisciplinary teams, and belief changing (Gordon, 1961) were also used.

The intrinsic causes of fixation were managed through the use of incubation periods (Smith & Linsey, 2011), problem reformulation (Linsey, 2010; Zahner, 2010), timely warning (Luchins, 1942), diversifying personality type (Toh et al., 2012) and teamwork (Linsey, 2010 & Crilly, 2015).

Youmans (2014) suggested another categorization of treatment methods based on the type of fixation. In Youman classification, unconscious fixation can be treated by means of timely warning (Luchins, 1942), use of physical prototypes (Youmans, 2010), and visual analogy (Casakin & Goldschmidt, 1999). On the other hand, incubation (Smith & Linsey, 2011), and design training methods such as TRIZ (Altshuller, 1994) and computer assisted designs (Dong & Sarkar, 2011) were suggested as treatment methods of conscious fixation (functional fixedness). The intentional fixation was found to be the hardest type of fixation to be treated because it is linked to fear of failure consequences. Some possible remedies that were suggested to manage intentional fixation involved the use of a cognitive information feedback systems (Youmans & Stone, 2005), interdisciplinary collaboration, creativity exercises, and changing beliefs (Gordon, 1961).

It is mentioned that the intuitive ideation methods, mainly morphological analysis (Wood, 1999) and brainstorming (Taylor, 1958), were suggested to treat fixation resulting from same and closely related problem domains, respectively, (Youmans, 2014).In contrast, the logical ideations methods such as TRIZ (Altshuller, 1994) and Synectics (Gordon, 1961), are preferred to be used for treating fixation caused by distance related problem domain and universal knowledge domain, respectively (Youmans, 2014).

Fixation assessment methods

Most design fixation studies relied on the use of hand sketches as a tool to visualize designer ideas (Moreno et al., 2015), and few combined sketches with model making (Youmans, 2011). Those sketches were generally self-assessed by participants themselves or by consulting experts to detect, assess and measure fixation (Moreno et al., 2015). Further, several metrics were commonly used to measure fixation and its effect on ideation including percentage of fixation , novelty , originality , variety (i.e. number of non-redundant ideas), and quantity and quality of solutions (Moreno et al., 2015; Shah, 2003). Generally speaking, a higher degree of fixation is believed to result in lower novelty, originality and variety of ideas. In many cases, surveys and questionnaires were also used to assess fixation indirectly, wherein participants and/or judges were asked about their awareness and perception of fixation.

Overall, researchers have extensively discussed design fixation, in term of its cause, mitigation methods, and its effect on ideation. The effect of design fixation on the quality of ideas were only slightly investigated in the literature, in other words, no one tried to look at the effect of design fixation on feasibility of the design ideas. Additionally, the effect of high complexity design problems and manufacturing requirements on fixation were not scrutinized in literature.

Migration tools

In literature, different designs strategies and methods have been developed to help designers build and modify designs for low cost conventional manufacturing. One of the oldest methods is the Boothroyd and Dewhurst (1983) Design for Manufacturing (DFM) method. Boothroyd and Dewhurst' DFM method is a set of guidelines that help make designs easier to manufacture with conventional processes. These guidelines are manually used with a set of worksheets to help designers modify and/or decompose their parts into simpler and easier to manufacture components that can be assembled later to build a more complex design. The Boothroyd-Dewhurst DFM tool provides detailed information related to design manufacturability time and cost in tabular format or 2D charts.

Later, researchers developed tools that can automatically locate the features or areas in a design that need modifications. These tools analyze designs given a specific manufacturing process and provide feedback in the form of warnings when features violate a set of predefined constraints (Tenenbaum & Cutkosky, 1992), or as a ranking for manufacturability of design features where features with lower scores are possible candidates for redesign (Yannoulakis, Joshi, & Wysk, 1994; Warnecke & Bassler, 1988). Other tools relied on performing complex manufacturability analysis of a design based on a predefined set of capabilities given a certain manufacturing process and provided results in textual format (Madan, Rao, & Kundra, 2007; Lockett, 2005; Ravi, 2003; Er & Dias, 2000) or as 3D colored feedback within the CAD system (Geometric, 2009; DFMA, 2015; Cast Designer, 2015), or as a portable 3D color coded PDF (Traband, 2013; Hoefer, Chen & Frank., 2017). Overall, these tools were tailored based on their designers' requirements (Satyandra, Das, & Nau, 1997) and in light of given manufacturing processes, mainly casting and machining. Therefore, the efficiency of these tools in facilitating design modifications depend largely on the quality and comprehensiveness of the feedback and the ability of the designers to interpret it.

On the other hand, some researchers-built process selection interfaces to help designers select the best process for manufacturing their designs. In these interfaces, the design is usually assessed against a set of manufacturing processes including both conventional and AM processes. Different decision-making tools such as Multicriteria decision making (MCDM) (Masood& Soo, 2002), Analytical Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOSIS) (Byun & Lee, 2005; Panda1, Bibhuti & Deepak, 2014) and Fuzzy-AHP (Akarte, Ravi & Creese, 1999; Munguian et al., 2010; Er & Dias, 2000) were used for assessment in these interfaces. These interfaces presented results as ranking of the manufacturing process, where the manufacturing process with the higher score represents the more favorable process for producing a design. Although the process selection interfaces can be used to determine which process is easier to convert the design to, it provides no indication on how to modify designs for that purpose.

Overall, currently available methods are a combination of manufacturability assessment and/or process selection. These methods are usually process specific, some of them have a difficulty of knowledge gathering, coding and updating and the rest are based on evaluating a design using common decision-making methods to select manufacturing process. These methods lack direct design suggestions and automatic modifications, and none of them work as migration tools from AM to conventional processes. Therefore, there is a need to develop a method that will allow designs to migrate from AM to conventional processes.

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A STUDY OF DESIGN FIXATION RELATED TO ADDITIVE MANUFACTURING

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Abstract

This study aims to understand the effect of additive manufacturing (AM) on design fixation. Whereas previous research illustrates the positive aspects of additive manufacturing, the overarching hypothesis of this work is that it might also have negative effects with respect to conventional manufacturability. In this work, participants from two groups, a Design for Conventional Manufacturing (DfCM) group, and a Design for Additive Manufacturing (DfAM) group were asked to design a basic product. Then, a second iteration of the design asked both groups to design for conventional processes; to include subtractive and formative methods like machining and casting, respectively. Findings showed that the DfAM fixated on non-producible manufacturing features and produced harder to conventionally manufacture designs, even when told specifically to design for conventional manufacturing. There was also evidence that the complex designs of the DfAM group limited their modeling success and seemed to encourage them to violate more design constraints. This study draws attention to the negative effect of AM knowledge on designers and provides motivation for treatment methods. This is important if additive manufacturing is used in prototyping or short run production of parts that are slated for conventional manufacturing later. The issue of design fixation is not a problem if Additive Manufacturing is the final manufacturing method; a more common practice nowadays. This work suggests that one should consider the possibility of fixation in design environments where AM precedes larger volume conventional manufacturing.

Keywords: Design for Conventional Manufacturing (DFCM), Design for Additive Manufacturing (DfAM), Design Fixation

Introduction

Engineering design is the art of visualizing, developing and building ideas to satisfy a set of customer requirements. According to Dieter [1], the design phase can be outlined in six steps including need identification, problem definition, information gathering, conceptualization, evaluation, detailed design and communication of design. Design is considered a critical phase since decisions can drive more than 70% of part cost. Greater efforts are usually spent at this early stage to avoid design failure at downstream activities [2, 3]. Design failure is often related to poor functionality, low quality, high cost, or late time to market [4]. These reasons of failure are often considered manufacturability issues that were not considered during design. Therefore, methods such as design for manufacturability (DFM) are used help designers consider manufacturing capabilities early during the design phase [4–7]. The use of DFM was facilitated with the introduction of Rapid Prototyping (RP) technologies [8–10]. These technologies, today called additive manufacturing (AM), enabled production of physical prototypes automatically from the 3D computer models layer by layer [12]. Rapid technologies spread widely because of their ability to produce highly complex parts without tooling, using little human intervention, with less material waste [12, 13]. However, due to material, size, durability and accuracy limitations, they were primarily used as design support tools to accelerate product development and reduce cost, leading to better customer satisfaction [12, 14]. The advancement of these technologies, in both materials and accuracy, has led to actual production use of AM parts, changing the use from merely prototyping to a mainstream manufacturing option. The use of additive technologies as a manufacturing process allows designers to essentially ignore design complexity as being problematic. In other words, AM encourages designers to ignore DFM restrictions while designing because of the freedom they provide by being a layer-based manufacturing process. As shown in Figure 1, a design that was previously considered impractical or impossible to build is now a viable option, depending on price and volume. However, if we consider a scenario in which the designer has not initially considered the transition to mass production, such as in the case of new products that were not intended for mass production, then what happens if the product is a success in the market, demand rises drastically, and we need a higher throughput conventional process? The contradictory manufacturing capabilities of AM versus conventional production processes could complicate the designer role when modification or re-design is needed. For example, if the designer is fixed on their initial AM-enabled designs, then there could be a delay in or failure to make the transition. Therefore, there is a strong motivation to investigate if there is such a negative effect of AM technology knowledge on the design process; something lacking in the current literature.

Considerable research has focused on the advantages of AM in providing more design freedom [15–19] and enabling mass customization [17, 20, 21]. If a conventional process like casting is to be used, it is usually required to have draft on surfaces, limits on wall thickness, no reentrant geometry and numerous other geometric restrictions because of pattern/mold tooling. However, with AM no tooling or a mold is required to produce a part, hence these restrictions generally do not exist [17, 18]. This has bolstered the role of AM in shortening the design process and accelerating product development [22]. However, the negative impact of AM on the design process is largely not discussed in literature, in particular, the issue of *Design Fixation*.

Fixation was initially mentioned as a psychological inertia that impedes personal creativity and problem-solving ability, resulting from cognitive adherence and/ or bias to preexisting knowledge [22–24] . In the context of design, fixation was defined as being the overreliance on the features of preexisting designs [26]. Qualitative studies discussed that fixation can be caused by organizational factors like project time/cost constraints, or precedential factors, like exposure to prior art or bias to initial solutions [25]. The effect of prior art and designer's commitment to initial solutions were extensively investigated in [27] where fixation was encouraged by precedential factors that can be either intrinsic and/or extrinsic to the designer. The discussions of intrinsic causes mainly included designer expertise[28], familiarity of domain knowledge [28, 29], age [31], personality traits [32] and standardization of design methods/process.

The extrinsic factors studies relied on exposing subjects to external stimuli such as preexisting solutions using different levels of abstraction of stimulus at different points of time [32, 33].

Design fixation studies relied on the use of hand sketches as a tool to visualize designer ideas [27], and a few combined sketches with model making [34]. Those sketches were generally self-assessed by participants or by consulting experts to detect, assess and measure fixation [27]. Several metrics were commonly used to measure fixation and its effect on ideation and creativity including percentage of

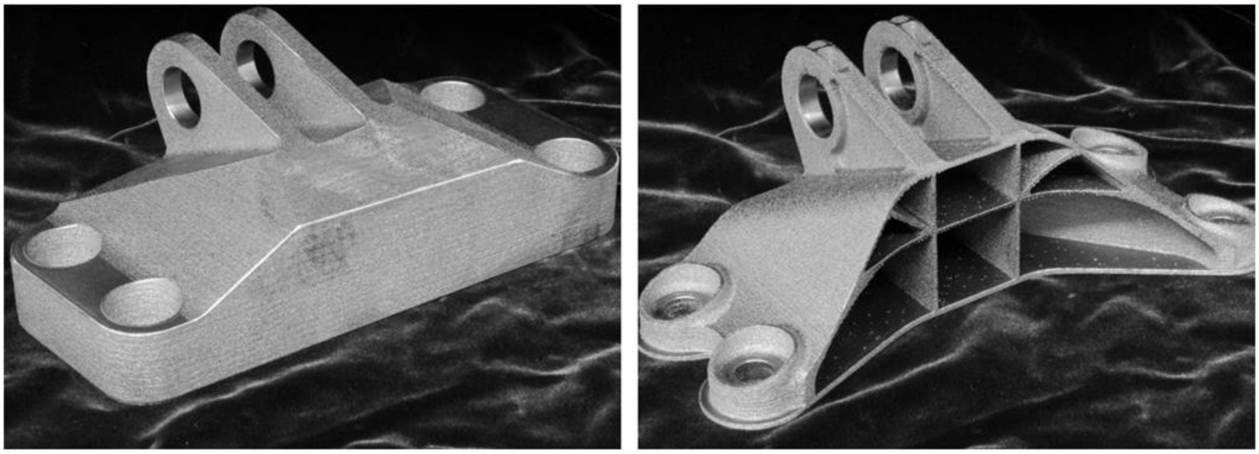

Fig. 1 Effect of manufacturing process selection on design complexity, jet engine bracket designed for conventional processes (left), and same jet engine bracket designed for additive manufacturing technologies (right). Photo courtesy of General Electric, used with permission.

fixation, novelty, originality, variety (i.e. number of non-redundant ideas), quantity and quality of solutions [22, 26, 27]. Generally, design fixation was found to result in lower novelty, originality and variety of ideas, therefore impairing creativity.

This paper will investigate the impact that AM knowledge might have on the design process, perhaps in a negative manner. Accordingly, this paper attempts to understand the effect of additive manufacturing on; design creativity, the design for manufacturability skills of designers, design fixation, designer experience, and a perceived freedom to design parts with nearly unlimited complexity.

Methods

In this work, two experimental conditions were used; a Design for Conventional Manufacturing (DfCM) group and a Design for Additive Manufacturing (DfAM) group. Both groups were given an initial design for manufacturability training session. After training, the DfAM group was asked to design a part considering that additive manufacturing will be used as the manufacturing process. The DfCM group was asked to design their part so it could be manufactured with conventional manufacturing processes, in this case, casting and/or machining. Participants from both groups were asked to self-assess their designs and then were asked to modify their previous designs to make them easier to manufacture using conventional processes of casting or machining.

Design problem

All participants were asked to generate concepts for a can/jar opener for people with arthritis. The opener was to make up of a single component and should be able to open ring cans, pop bottles, glass jars and plastic bottles. Within the design brief, a list of customer requirements and constraints were included (Table 1), where the only difference for each group was the type of manufacturing. The design challenge was chosen to represent a real-life problem but in a simple component design. The participants' familiarity with the design problem was questioned using a post experiment interview. Six participants (4 in the DfAM group and 2 in the DfCM group) reported that they had previous partial exposure to the design problem. Three of them were exposed to the elderly ring can opener problem, two for the elderly jar opening and one for arthritic jar opening. Their exposure was believed not to affect results because they were generally distributed among the two groups [28].

***Customer*:** People with Arthritis

Problem statement: For people with arthritis in their hands or fingers, every day is a challenge. A simple daily task like putting on a seatbelt or opening a jar is a big problem. Opening a jar with hand grip or a can with an opener involves a twisting motion; which is considered painful or impossible for those with arthritis. The pain associated with the use of the hand or fingers while opening is due to joint damage that causes functional disability. Statistics show that a person with arthritis has on average only 40% of normal power and pinch grip within six months of diagnosis, even with early commencement of medications. Therefore, an assistive device to substitute grip weakness and lack of hand strength to help in opening jars, bottles, and cans is required.

Design Statement: Design an opener that will allow Arthritis patients to open ring cans, pop bottles, jars and bottles easily with no pain.

Design Criteria/requirements: 1) Should open ring cans, plastic bottles, pop bottles and jars, 2) Should open different jars and bottle sizes within the range specified in constraints, 3) Safe opening; it should grip the lid/cap securely without slipping while opening

Constraints: 1) Should be a single component, 2) Should open a jar with lid diameter range from 1.5in - 4.5in, 3) Should open a bottle with lid diameter range from 1in - 2in, 4) Should fit people with different grip size range from 4in - 6in, 5) Final design should fit in a bounding box of 10in x 5in x 2.5in

Deliverables: Hand sketches, 3D CAD models and descriptions/comments

Fig.2 Design Brief

Experiment Conditions

DfCM Group

Participants in the design for conventional manufacturing group were given a design for manufacturability session and the design brief. Next, they were asked to generate as many ideas on paper as they can, given that either casting or machining would be used. They were encouraged to write any comments or descriptions on sketches to communicate their ideas and then to transfer their best idea to a 3D model using SolidWorks. After modeling, they were asked to self-assess and modify their designs to make them easier to manufacture using machining or casting.

DfAM Group

Participants in the design for additive manufacturing group were given the same design brief and asked to do the same as the conventional group, with a few differences. First, they were given the same design for manufacturability sessions, but then were exposed to images of complex parts produced with additive manufacturing, and they were educated about the design freedom AM provides in creating very complex single or multi-material parts. They were given the same design brief and asked to generate as many ideas as they can, given that additive manufacturing would be used. They were encouraged to write any comments or descriptions on sketches to communicate their ideas and then transfer their ideas to SolidWorks. After modeling, they were told to imagine that their designs were successful and demanded in mass quantities, and they were asked to self-assess and modify their designs to make them easier to manufacture, now using casting or machining.

Hypotheses

Previous qualitative studies highlighted that designers who create designs for additive manufacturing tend to ignore design for manufacturability guidelines (constraints) and actually create complex designs that are often impossible to be produced with conventional processes [15, 17–19]. Therefore, the notion is that designers who design for additive manufacturing will produce more novel and functional designs, with higher design variety and harder to manufacture designs compared to those who design for conventional processes. Hence, the proposition is that designers who design for additive manufacturing initially will *fixate* on non-producible features (e.g. undercuts, sharp corners, thin wall sections, internal cavities, deep depressions, no draft, etc.) when asked to modify their designs for conventional manufacturing.

In this study, four hypotheses were used to investigate the effect of additive manufacturing on designer skills, as follows;

Hypothesis1: Designers who design for additive manufacturing will create more novel, more functional and harder to manufacture designs than those who design for conventional manufacturing.

Hypothesis2: Designers who design for additive manufacturing will fixate on non-producible features when redesigning for conventional manufacturing compared to those who firstly design for conventional manufacturing, and consequently, that their modified designs will be harder to manufacture than DfCM-modified designs.

Hypothesis3: Designers who design for additive manufacturing will be frustrated more and will experience more difficulty when redesigning a part for conventional manufacturing than those who design for conventional manufacturing first.

Hypothesis 4: Designers who design for additive manufacturing will be less successful in transferring sketches to 3D models than those who design for conventional manufacturing.

Participants

Twenty-six engineering students (four females, and twenty-two males) with ages from 18-35 participated in this experiment. Participants were randomly assigned to groups resulting in thirteen participants per group. Ten participants, evenly distributed among groups, stated that they had a previous experience with DFM, whereas thirteen participants (seven in the DfAM group and six in DfCM group) claimed previous knowledge/training with DfAM. Also, all participants indicated that they had previous design experience. Most of them reported that they liked designing, except for three (two in conventional group and one in additive). Participants were asked to assess their modeling skills with SolidWorks on a scale from 1-10. Students in the conventional group were found to have a modeling skill level of 4.77 (2.77) compared to 6.34 (1.26) for those in the additive group.

Procedure

The experiment was conducted in a closed lab room to minimize distraction. One subject per each experimental session was tested at a time. The experiment started by giving participants an overview of the experiment purpose and procedure. Then, they were given a consent form to sign and filled out a demographic survey. Participants were then assigned to one of the experiment conditions. This was followed by a design for manufacturability training session. The design for manufacturability training educated participants about DFM approaches, goals, guidelines, and general design rules/restrictions considered when designing for conventional processes. The training was supported by images of what should and should not be done when considering conventional processes for manufacturing. In addition to DFM training, participants in the DfAM group were educated about AM and the advantages AM provides to designers in terms of design freedom. This was supported by showing images for complex parts produced by AM.

Then, participants were asked to read the design brief/problem and were shown images of the different cans, jars and bottles they would be designing the opener for. The design problem was explained verbally by the researcher once again to ensure their understanding, wherein, their attention was drawn toward satisfying the design requirements and constraints listed in the design brief. The participants were then given plain paper and asked to generate as many ideas as they could. Participants were asked to comment and write descriptions to clarify and communicate their ideas/sketches. Subjects in the conventional group were asked to design their parts given that they will be produced using conventional processes, namely, casting or machining. In contrast, those in additive group were told that their parts would be produced using AM.

Once the idea generation task ended, participants were asked to transfer their favorite idea to a 3D model using SolidWorks. After a modeling session, participants in the DfAM were asked to imagine that their designs succeeded and now demanded mass quantities. Based on that, they were asked to self-assess and modify their previous designs to make it easily manufacturable with conventional processes. The conventional group was also asked to self-assess and modify their designs to make it even easier to manufacture using conventional processes. Then, all participants were asked to apply modifications to their 3D SolidWorks models. Lastly, participants were interviewed. Examples of the ideas created by participants and the 3D models are shown in Fig. 3.

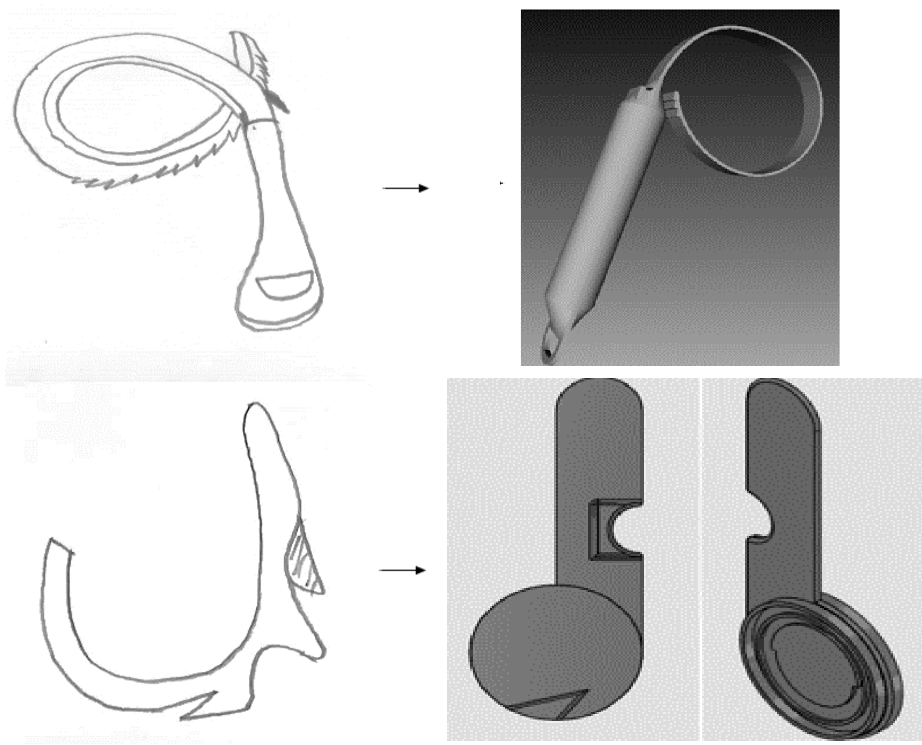

Fig. 3 Examples of ideas by participants hand sketches (left), and 3D CAD models (right).

Dependent Variables

To evaluate the effect of additive manufacturing on designer performance, different dependent variables were used (Table 1). These variables were: 1) design creativity, 2) Quality of modified design, 3) design fixation, 4) designer experience and 5) freedom of design complexity.

Table 1 Dependent variables and associated metrics

	Dependent variable	Measures
Hypothesis 1	Design Creativity	Design Novelty, Functionality (Design Quality), Manufacturability of original designs (Design Quality)
Hypothesis 2	Quality of modified designs	Manufacturability of modified design
	Design Fixation	Number of non-producible features generated in modified design concepts, Fixation percentage
Hypothesis 3	Designer experience	Frustration score, Redesign Difficulty score
Hypothesis 4	Freedom of design complexity	Success percentage in modeling ideas/designs, Percentage of participants reporting that modeling skills affected their designs

Design creativity. Design creativity was based on a method developed by Shah (2003) to evaluate creativity for groups of ideas. In this study, creativity was measured by the ideas novelty, and quality.

Novelty was calculated based on a method proposed by Shah [35] and updated by Oman [36], wherein the design concept is decomposed to its key functions (requirements) and form (features). This is followed by mapping each of the key functions to its features (sub-solution) within the concept. This process was

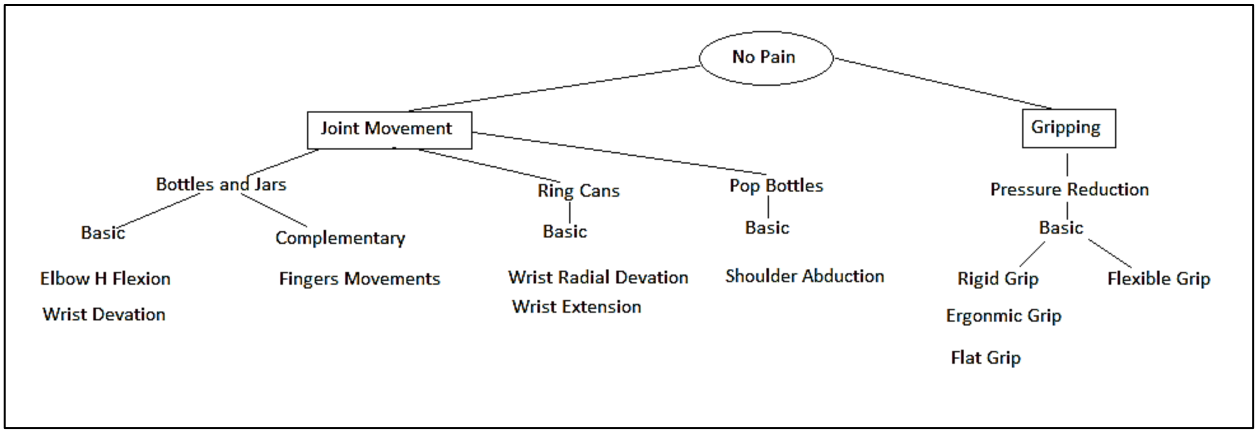

Fig. 4 Part of the Genealogy tree for the DFCM group indicating opening without pain function

repeated for each concept and the final concepts' function to form (genealogy) tree was obtained. A portion of the genealogy tree based on the conventional group's design is shown in Fig.4.

The infrequencies of each sub solution for each sub function were used to calculate a novelty score for that solution. Then, novelty scores were calculated based on Shah's method (2003). The weights (f) assigned for each of the three main functions for the purpose of novelty score calculations were 0.6, 0.1 and 0.3, respectively.

Design Quality was measured by two metrics; *functionality* and *manufacturability* of design. The functionality of ideas measures the degree to which a design meets requirements and constraints. Each concept was decomposed to its sub-solutions. The degree to which a sub-solution is satisfying the corresponding function was evaluated and then the overall functionality score was calculated using a weighted multi-criteria evaluation method.

The manufacturability of designs can be measured based on an absence of a set of common non-producible features for a process. In the case of machining, examples include features such as: enclosed cavities, tight tolerances, thin sections, severe undercuts, internal sharp angles, deep depressions, etc. The equation used to calculate manufacturability of designs was:

$$M = 10 \times \frac{Nt - Nc}{Nt}$$

Where M is the manufacturability score, Nt= Total number of non-producible features for a particular process, and Nc is the number of non-producible manufacturing features noticed in the design. Each design was assessed in terms of castability and machinability, and then both scores were averaged to produce a conventional manufacturability score.

Design Fixation. Design fixation was used to assess the negative effect of additive manufacturing on design for manufacturability skills of the designer. The ideas were assessed based on the presence of a set of non-producible features in initial and modified designs. Then, fixation was measured by the number of non-producible features transferred /generated by the designer in the redesigned versions. The percentage of non-producible features transferred was also used to test the correlation between the manufacturability score of modified designs and transferred non-producible features. Fixation percentage was calculated by dividing the number of transferred features over a total number of previous features [27]. To understand the participant's awareness of the fixation, they were asked during post experiment interviews whether they considered design for manufacturability guidelines while modifying their designs.

It is worth mentioning that two judges were consulted to further validate and avoid any biases while assessing design creativity and fixation measures. The judges performed the evaluation independently and their assessment results were treated equally. The judges were mechanical engineers who have a professional design and manufacturing experience. The experiment goals were not declared to the Judges to avoid biases. Before the assessment session, the evaluation method was explained by the researcher to the judges and then they were given a trial to practice the evaluation. After that, they were asked to answer questions on how well each of the requirements stated in the design brief was achieved [36, 37]. For example, the functionality of designs was assessed by questions such as "Will this design help to open ring cans, pop bottles and jars with no pain?", "Will this design help to open plastic bottles and jars with different lid sizes?", …etc. The evaluation scale ranged from 1-10, where 1 meant "strongly disagree" and 10 "strongly agree". The functionality sub scores were then aggregated to obtain the overall score for the design solution as described in Shah [35]. The inter-rater agreement analysis between the judges was then implemented using Pearson correlation tests. The correlation tests of the judges' scores indicated a strong consistency between raters (r=0.91).

Designer Experience. The effect of additive manufacturing on designer experience was also measured by two metrics; degree of designer frustration and redesign difficulty. Both frustration and redesign difficulty were measured using a Likert scale during the post experiment interview. Participants were asked to rate their frustration degree, if any, and to specify when and why they felt frustrated. The difficulty of redesign was further investigated by asking them whether they thought that considering AM as a manufacturing process while designing initially made it harder or easier to redesign parts for ease of manufacturing later. Also, they were asked whether they found it harder or easier to apply skills they learned and to specify which skill they would prefer to use in the future and why.

Freedom of Design Complexity. The design complexity limits that can be created for AM processes was measured using two metrics; the success percentage in modeling ideas and percentage of participants who reported that their modeling skill level negatively affected their ability to transfer designs to 3D models. It was proposed that AM provides designers with significant freedom to create designs with unlimited complexity that would normally be impossible with conventional processes. The negative effect of this freedom was also assessed by the percentage of design constraints that were violated while designing. These metrics were further investigated by asking participants what they did and did not like about DfCM and DfAM to understand the effect of conventional design restrictions and AM freedom on limits of design complexity.

Results

In this paper, both positive and negative effects of additive manufacturing on design were studied. Novelty and quality in term of functionality were studied. Results are shown in the following sections.

Effect of additive manufacturing on design creativity

Novelty

To test the effect of AM on design novelty, a one tailed t-test was conducted. The results showed that the DfAM group created significantly more novel designs than the DfCM group (t (1, 24) = 2.66, $p<0.01$), as shown in Fig.5. The results supported the hypothesis that designers for AM produced more novel designs than those who designed for

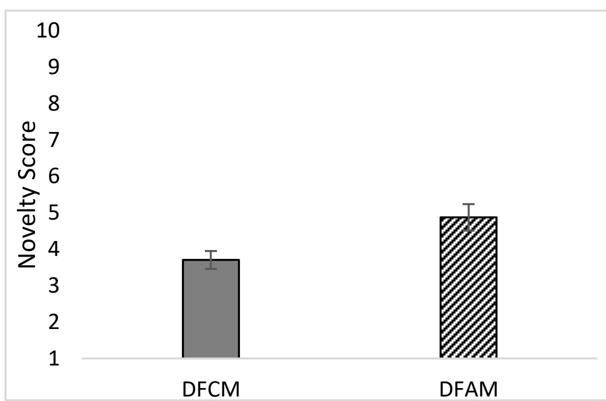

Fig. 5 Average novelty score for designs created by conventional versus additive group. Error bar represents ±1standard error.

conventional processes. The novelty score for the additive group was on average 4.87(1.31) compared to 3.7(0.885) for the conventional group. The data satisfied both normality and variance equality assumptions.

Functionality

The quality of designs in term of functionality for both groups were analyzed using a two-tailed test. The test revealed that the functionality of designs created by the conventional group did not differ from the functionality of designs produced by the additive group; (4.55 (1.25)) vs (4.83 (1.48)), as shown in Fig. 6. To investigate whether the functionality of designs was affected by novelty, a within-group Pearson correlation testing was conducted. The analysis indicated a significant positive correlation between design novelty and functionality within each group, $r_{DfCM} = 0.645$, $p<0.01$ and $r_{DfAM} = 0.642$, $p<0.01$. Thus, the higher the novelty of designs, the more functional they may be.

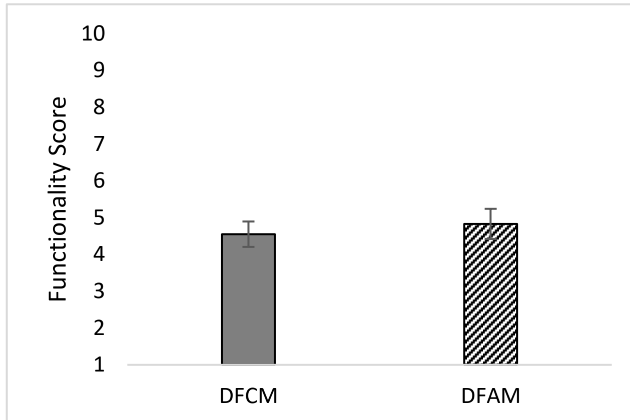

Fig. 6 Average functionality score of designs created by conventional versus additive group. Error bar represents ±1 standard error.

Conventional manufacturability of original design

The ease of conventional manufacturing of a design is another indicator of the quality of the designs that represent the second dimension of design creativity. To understand the effect of design for additive manufacturing on ease of manufacturability, a one tailed t-test was used to compare the manufacturability scores. It was

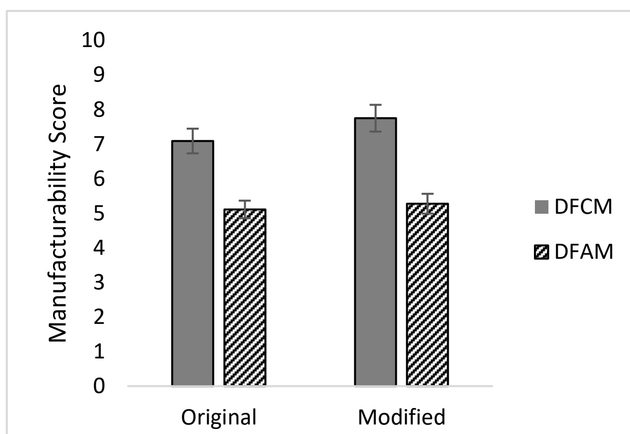

Fig. 7 Average manufacturability score of designs created by conventional and additive groups (both original and modified). Error bar represents ±1standard error.

found that the DfAM group (5.1 (0.92)) created significantly harder to manufacture designs than the DFCM group (7.1 (1.3)), t (1, 24) = 4.52, $p<0.01$ (both original and modified designs), as shown in Fig.7. These results suggest that design for AM will reduce the manufacturability of the designs with respect to conventional processes, which should be expected. Data were normally distributed and had homogenous variances. A positive correlation was observed between functionality and manufacturability of designs for the DfCM group only, $r_{DfCM}=0.548$, $p=0.052$; the higher the functionality the better the manufacturability of designs. Examples of designs created by both groups are shown in Fig.8.

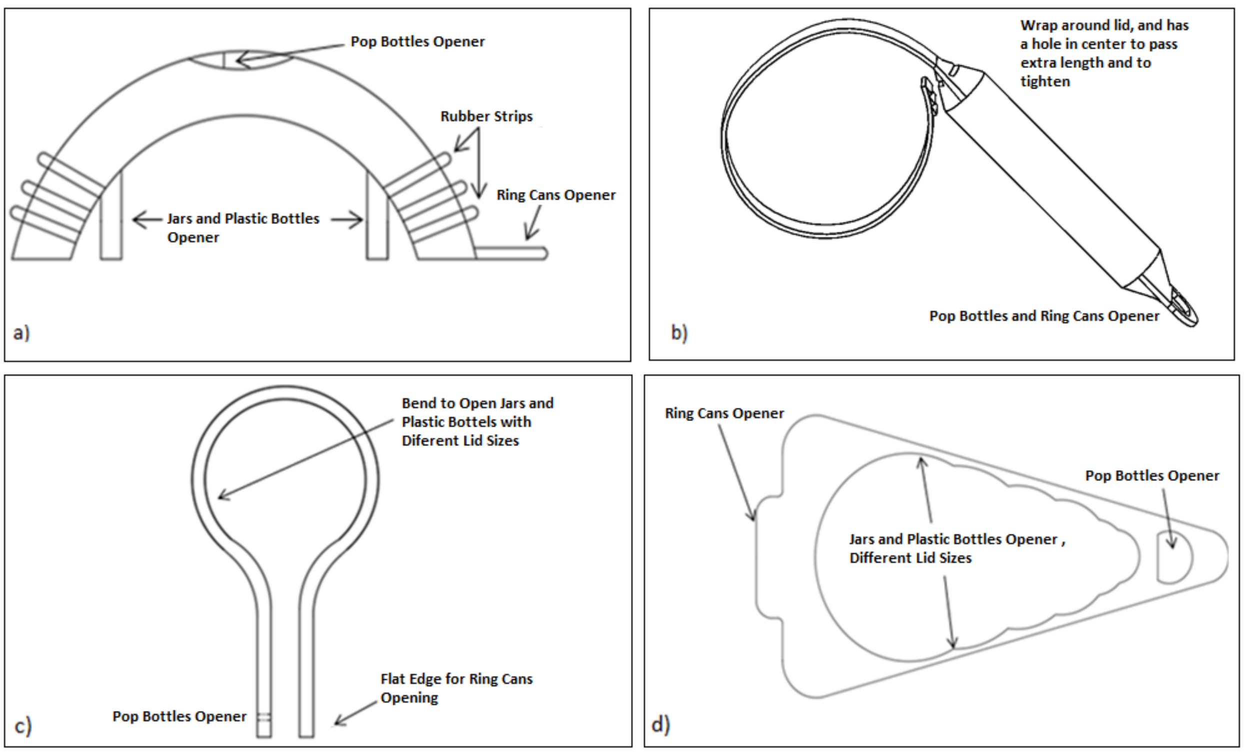

Fig. 8 Examples of designs created by the DfAM group (a, b) and the DfCM group (c, d).

Additive manufacturing and DFM designer skill

The effect of additive manufacturing on design for manufacturability skills was assessed using two metrics; manufacturability score of modified designs and design fixation.

Conventional manufacturability of modified designs

To understand the effect of additive manufacturing on design for manufacturing skills of designers, both groups were asked to modify their original design to make them suitable for production using conventional processes. Then, the conventional manufacturability scores of their modified designs were calculated and compared between groups using a one-tailed t-test. As in their original designs, the DfAM group (5.3 (1.03)) produced significantly harder to manufacture modified designs compared to the DfCM group (7.75 (1.4)), $t(1, 24) = 5.14$, $p < 0.001$, as shown in Fig.7. To examine whether the conventional manufacturability of original and modified designs within the DfAM group differ, a paired t-test was used. The results indicated that the conventional manufacturability of the original designs did not differ from modified designs within the DfAM group, $t(2, 13) = -1.15$, $p > 0.1$. In contrast, a paired t-test for manufacturability scores of original and modified designs within the DfCM group showed that the manufacturability of modified designs differed significantly from original designs, $t(2, 13) = 2.31$, $p = 0.04$.

It is worth mentioning that a Pearson correlation test was conducted to assess the relationship between novelty, functionality and manufacturability of modified designs for each group; as the dimensions of creativity. It was found that the functionality and manufacturability of designs created by the DfCM group were strongly related, $r_{DfCM} = 0.59$, $p = 0.034$. Increasing functionality of DfCM designs was correlated with an increase in their manufacturability.

Design Fixation

To verify whether designers who design for additive manufacturing show evidence of fixation on non-producible features, the mean number of non-producible features in original and modified AM designs was compared using a paired t-test. The results indicated that the number of non-producible manufacturing features in original AM designs did not differ from those in modified designs (Figure 9), with $t(2,13) = 1.15$, $p = 0.273$.

Thus, designers in the DfAM group fixated on non-producible features of their initial designs during redesign. This is interesting due to the fact that both the additive and conventional groups were taught the same DfCM principles, suggesting that once the designers allowed themselves to design for AM, it was difficult to change. To understand the relationship between fixation on the non-producible features of the additive group's modified designs, the percentage of non-producible features transferred to modified designs were first calculated and then a correlation test was implemented. The results revealed that the % non-producible features transferred and conventional manufacturability of modified designs in the additive group have a negative correlation coefficient r_{DfAM}=-0.497, however the p=0.084 indicates that they are not significantly correlated.

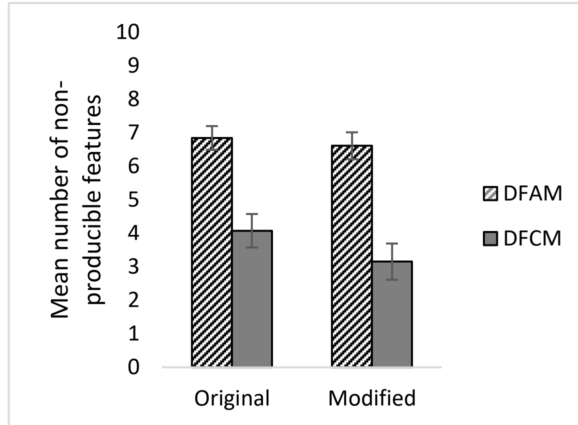

Fig. 9 Average number of non-producible features in designs. Error bar represents ±1 standard error.

Similarly, a paired t-test was used to investigate whether the conventional group experienced fixation. Fixation was not evident in the conventional groups, as it was found that the number of non-producible features between original and modified designs differed significantly, t (2, 13) =2.3, p=0.04, (Figure 9).

Effect of additive manufacturing on designer experience

Designer Frustration

To test the effect of design for additive manufacturing on designer experience, designer frustration between groups was examined. The Rayan Joiner's test of normality showed that the data is not normal, whereas Levene's test indicated that variances are homogenous. Therefore, Mann Whitney non-parametric testing was used to analyze the data. The analysis revealed the degree of designer's frustration did not differ between additive and conventional groups (U=156, p = 0.3299), as shown in Fig.10.

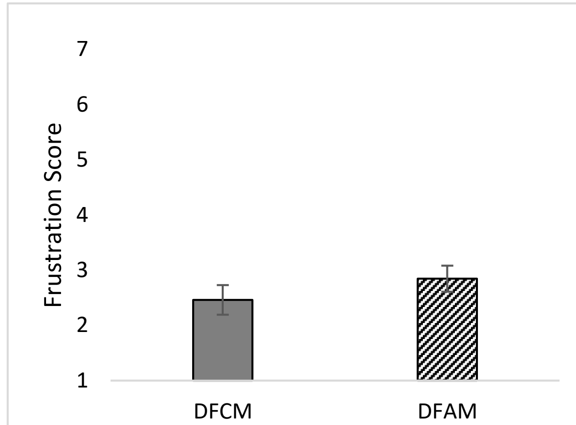

Fig. 10 Average frustration score for DFAM group vs DFM group. Error bar represents ±1 standard error.

The interview results indicated that sources for additive group frustration were 38.5% from ideation, 15.4% from re-design and 23.1% from 3D modeling. In comparison, the conventional group became frustrated on the order of 23.1% from 3D modeling and 38.5% from ideation while no one in the conventional group indicated frustration due to redesign. These percentages are based on particpiants' responses who only gave reasons for frustration during interview.

Redesign Difficulty

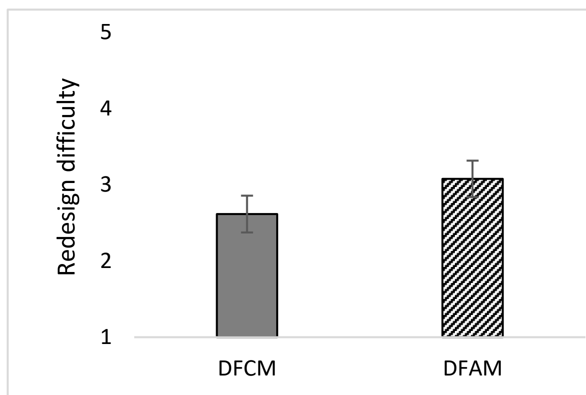

Fig. 11 Average redesign difficulty score for DFAM group vs DFM group (U = 159.5, p = 0.2133, one tailed). Error bar represents ±1 standard error.

The effect of design for additive manufacturing was also assessed by comparing redesign difficulty scores between the groups. As in the frustration data, the Rayan Joiner's test of normality showed that the data was not normal and Levene's test indicated that variances were not homogenous. Therefore, Mann Whitney non-parametric testing was used to analyze the data. The results in Fig. 11 illustrate that there was no difference in redesign difficulty scores between the additive (3.07 (1.32)) and the conventional group (2.52 (0.87)). However, interview responses indicated that 77% of participants in the additive group reported that considering AM initially made it harder to modify their designs later, where 25% of the additive group changed their designs completely in the re-design phase. In addition, 86% of additive participants stated that they would prefer to use DfCM in the future while designing instead of designing for AM in the first iteration. Furthermore, participants in both groups indicated that DfCM is more realistic and simple to apply if it is considered initially, though the restrictions imposed by it are challenging.

Freedom of design complexity

Success percentage in modeling ideas/designs

To test the effect of DfAM on freedom of design complexity, the percentage of successful 3D modeling between groups was examined. Mann-Whitney nonparametric testing was used to analyze the data because both normality and variances homogeneity assumptions were violated. The analysis showed the additive group was significantly less successful in transferring sketches to 3D models than the conventional group (Fig.12).

Percentage of participants reporting that modeling skill level affected their designs

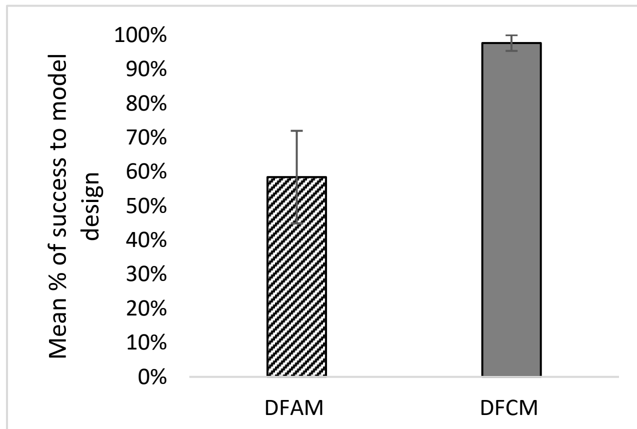

Fig. 12 Average success percentage in modeling designs for the DfAM group vs DfCM group (U=118.5, P = 0.0367, one tailed test). Error bar represent ±1 standard error.

Another metric used to test the effect of DfAM on freedom of design complexity was the percentage of participants reporting that their modeling skill level affected their ability to transfer sketches successfully to 3D models. Interview results showed that 83% of additive group participants stated that their modeling skill negatively affected the transfer of sketches to 3D models and 30% of those felt frustrated with modeling. Similarly, 83% of the conventional group participants reported that their modeling skill level affected their ability to transfer designs to 3D models and 33.3% of them felt frustrated with modeling. However, it was observed that 22% of the additive group changed their design completely when they modeled in 3D compared

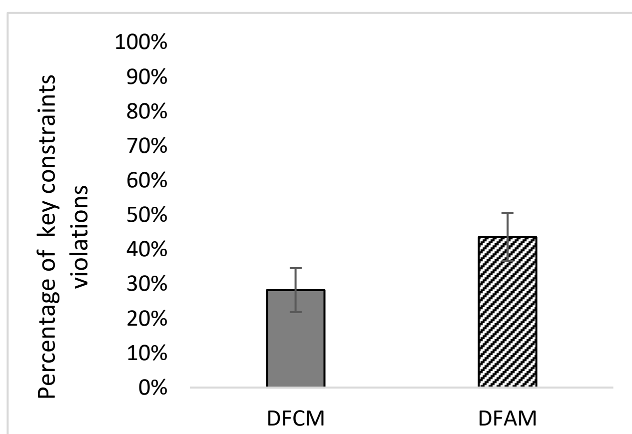

Fig. 13 Percentage of constraints violated DFAM vs DFM Error bar represents ±1 standard error.

to none of conventional group. Also, 36% of the additive group failed completely to create their models in 3D. Those in the additive group who reported that their modeling skills did not affect the transfer process, justified it by the simplicity of their designs.

Speaking of design freedom, all participants stated that they liked the freedom AM provides to explore and create more complex ideas while designing. However, it was observed that participants in the additive group actually tended to violate more design constraints (44%) compared to 28% of those in the conventional group (Fig.13). The nonparametric testing indicated that the percentages of the constraints violated by the additive group were not significantly higher than those constraints violated by the conventional group (U=56.5, p=0.079, one tailed). However, it may be worth investigating in the future whether design freedom is perhaps misused at the expense of the part design requirements**.**

Discussion

In this section, we review the 4 hypotheses proposed in this work and discuss the findings of the study.

With respect to Hypothesis1, does design for additive manufacturing have an effect on design creativity? In this work, design for AM was found to influence design creativity. To support that, it was hypothesized that a designer who designs for AM will create more novel, more functional and harder to manufacture designs than the conventional group. This hypothesis was partially supported, wherein results showed that the additive group created more novel, and harder to manufacture designs than the conventional group. However, the functionality of the designs did not differ between the groups. The higher novelty of designs from the AM group can be explained by the freedom that layer-based manufacturing provides, where designers do not need to consider the restrictions that are common with conventional manufacturing processes [16, 18]. This was supported by participants' responses to a question about what they liked about AM, where they reported that the freedom AM provided helped them explore more ideas and to create more complex designs. However, ignoring manufacturing constraints while designing for AM caused lower manufacturability of designs, for both the original (as might be expected), but also for modified designs;

even when the group was told to make changes for machining or casting. This brought to light what has been frequently found in previous qualitative studies about the positive effect of AM on increasing design creativity; true if the creativity was defined in term of design novelty. However, more caution should be taken when talking about the effect of AM on design creativity if the quality of design, manufacturability in particular, was also considered.

With respect to Hypothesis 2, does design for additive manufacturing impair the design for manufacturability skills of a designer and cause design fixation?

As hypothesized, it was found that the additive group produced significantly harder to manufacture modified designs than the conventional group. In fact, the manufacturability of the original and modified designs of the AM group did not differ. In other words, designers failed to make their designs easier to manufacture using conventional processes in light of the same DfCM training. In this manner, the additive group showed evidence of fixation, where they fixated on non-producible features of the original designs and transferred them to their modified designs. In contrast, there was no evidence of fixation among the conventional group.

The failure of the AM group to dis-attach from non-producible features can be linked to the *recency* of AM knowledge and the complex nature of AM designs. The AM group were educated about DFM firstly then about AM. After that, their first design was directed toward creating designs for AM where ignoring the manufacturing constraints was allowed or almost encouraged. This in turn further emphasized and could have enforced the activation of AM-related knowledge in their minds. Later, when they were asked to modify their designs for conventional processes, the strongly activated knowledge could have impaired their abilities to retrieve the DFM knowledge from memory. The activated knowledge could have acted as a mental/cognitive barrier, where the distraction effect of this recently activated knowledge (memories) inhibits retrieval of other inactivated memory [39]. Also, the complex nature of AM designs emphasizes the recency effect because it required the AM group to perform more extensive changes which in turn increase the cognitive demands and the distraction effect in memory to retrieve DFM knowledge and detect non-producible features simultaneously, causing fixation. Participant responses from the AM group provide an additional support to this where they stated that considering AM as a manufacturing process on the first iteration made it harder to modify their designs for ease of manufacturing using conventional processes. Similarly, the recency of DFM knowledge and generally more simple nature of their designs might explain the absence of fixation in DfCM group. It should be noted, that participants in the AM group were not aware of their fixation, where 92% of them reported that they considered the DfCM restrictions while modifying their designs, which strongly opposed the results obtained from their designs.

With respect to Hypothesis 3, do designers who design for additive manufacturing show evidence of frustration and redesign difficulty?

The results indicated that the DfAM group did not show evidence of design difficulty or frustration. However, the interview feedback contradicted these findings with regard to re-design difficulty, where 77% of them indicated that designing for AM made it harder to modify their design later for conventional processes. The difficulty of redesign can justify the preference of 86% of the additive group to use DFM principles while designing in the future even with the challenges associated with manufacturing constraints/restrictions. One interesting observation which further supports difficulty of modification is that 25% of participants within the additive group changed their designs completely (new designs) instead of modifying their old design. Changing designs completely is not desirable because of it will be received as a completely new design by stakeholders, potentially leading customer rejection [25] or further engineering change orders.

With respect to Hypothesis4, does AM provide designers with freedom to design parts with unlimited complexity?

Additive manufacturing was found to provide designers with design freedom but was limited by their ability to 3D model their ideas. Although participants of additive group indicated a higher modeling skill than the conventional group, they were less successful in transferring their ideas to 3D models compared to those in the conventional group. This is likely due to the higher complexity of designs from the DfAM group. This explanation can be drawn from responses of 36% of DfAM participants who failed to complete 3D model where they stated that they were "so ambitious while designing, making it too hard to 3D model their designs". In addition, the inability to model caused around 30% of the DfAM group to feel frustrated and forced 22% of them to change their ideas completely. Another interesting finding is the additive group violated design constraints approximately twice as often as the conventional group; potentially implying a *misuse* of their design freedom. One potential explanation is that trying to take advantage of design freedom to create more novel ideas, led them to unintentionally ignore the constraints they were given for the design problem itself. This was clear from their responses where all of them indicated that they liked AM freedom because "you do not need to be restricted to anything" and "have more freedom to explore ideas". In contrast, the restricted nature of the design process associated with conventional processes may have led the participants inherently toward handling requirements/constraints (both product and process), which may explain their higher degree of commitment to the formal design requirements.

Conclusion

Additive manufacturing obviously gives a designer a vast design space to think creatively and pulls the stops on what geometry can be physically manufactured. However, this research raises a question about the long-term effect on impairing the designer's skill in creating conventionally manufactured parts later. Results showed that design for rapid technologies causes designers to create more novel and harder to manufacture designs compared to DFCM. As hypothesized, DfAM was found to impair design for manufacturability skills, where it was found that designers fixated on conventional non-producible manufacturing features, leading to harder to manufacture designs even after re-design. Also, results indicated that the DfAM group was less successful in modeling their designs and violated more design constraints; suggesting a deeper negative impact in the form of a misuse of design freedom. The findings of this study bring awareness of the downside of design for additive manufacturing and may present an opportunity to develop treatment tools.

Future work may focus on treating design fixation caused by DfAM through modified use of DFM based software, which should integrate considering both rapid technologies like additive with more conventional manufacturing. In general, the field of design for AM is still underserved with respect to CAD modeling and analysis tools; with limited tools to model stochastic features like foams, gradient materials, integrated hinges, or simply complex geometry in general that is possible with AM. Future research may also focus on replicating the study with professional designers using more complex design tasks. It was apparent from this study that the same DFM training for both groups did not assist the DfAM group as much as it did the DFCM group. The overarching conclusion is that once a designer is allowed/asked to design for a rapid technology like AM, it might be difficult to modify that thinking. A future goal is to provide tools for enabling a better co-existence of DfAM and DFM, enabling better integration of additive manufacturing into the lineup of manufacturing methods available to design engineers.

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DESIGN FOR MANUFACTURABILITY-BASED FEEDBACK TO MITIGATE DESIGN FIXATION

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Abstract

This study assessed the effectiveness of 3D visual feedback from design for manufacturability (DFM) software on mitigating design fixation on non-producible manufacturability features. A fixation group and a defixation group were asked to design a basic product for additive manufacturing and then to modify the next iteration for conventional machining. The fixation group relied on their self-assessment while modifying, while the defixation group utilized DFM software feedback. Results showed that 3D feedback reduced design fixation on non-producible features and improved the machinability of modified designs. Findings suggest the use DFM software for treating the design fixation related to additive manufacturing and for facilitating migration of designs from additive to conventional manufacturing. This work could be applied to manufacturing industries, particularly where AM is used for prototyping, or when demand for part changes and an AM part needs to migrate to conventional methods.

Keywords: Design for Manufacturability (DFM), Design for Additive Manufacturing (DFAM), Design Fixation

Introduction

Designers are generally under pressure to quickly respond to market needs by introducing new products. One way to shorten the design process can be through the use of additive manufacturing (AM). In some cases, AM as a design support tool helps the designer to test the fit, form and sometimes function of their designs, while ignoring design complexity problems (Gibson et al., 2005; Mansour et al., 2003; Campbell et al., 2012). However, a recent study by the authors (Abdelall, Frank, and Stone, 2018) showed that designing new parts for AM may in fact impair design for manufacturability (DFM) skills of the designer. The effect of AM on impairing DFM skills materializes if demand for a new product increases to a degree that requires mass production with conventional manufacturing, which necessitates redesign for ease of manufacturing. In the same study, the authors found that the complex nature of AM produced parts combined with time constraints complicates the problem, causing designers to fixate on non-producible features of their designs. The problem of design fixation on non-producible features is detrimental because it can result in more redesign iterations before the part is suitable for mass production. Therefore, there is a strong motivation to treat design fixation caused by the use of AM as a manufacturing process.

Related Work

Fixation is considered as a type of a psychological inertia that hinders personal creativity and problem-solving ability, resulting from cognitive adherence and/ or bias to preexisting knowledge (Jansson et al., 1991; James et al., 1998; Crilly et al., 2015). In engineering design context, fixation is defined as the overreliance on the features of preexisting designs. Design fixation can occur unconsciously, consciously or intentionally (Youman et al., 2014). The unconscious fixation is related to *Einstellung effect*, where a designer blindly adheres to prior designs (Bilalić et al., 2016). Conscious fixation is linked to functional fixedness where designers are finding new uses for existing features to solve problems (Purcell & Gero, 1996). Finally, *intentional* fixation is related to the counter sunk effect where the path of least resistance is preferred to generate solutions (Viswanathan & Linsey, 2013).

Qualitative research stated that fixation can be caused by organizational and/or precedential factors. The organizational factors are mainly represented by project, time/cost constraints, and blame culture. The precedential factors include exposure to prior art, bias to initial solutions and client briefing (Crilly et al., 2015). The effect of prior art and designer commitment to an initial solution on fixation were extensively investigated in experimental studies (Moreno et al., 2015). Wherein, researchers suggested that fixation can be encouraged by precedential factors that can be either intrinsic and/or extrinsic to designers. The discussions of intrinsic causes include mainly designers' expertise (Linsey et al., 2010), or familiarity with domain knowledge (Purcell & Greo, 1996; Cross et al., 2004), age (Agogué et al., 2014), personality traits (Toh et al., 2012), and standardization of design methods/process (Crilly et al., 2015). The extrinsic factors studies relied on exposing subjects to external stimulus (i.e. preexisting solutions) verbally or pictorially (Jansson et al.,1991) or physically (Youmans et al., 2011) using different levels of abstraction for the stimulus (Cheng et al.,2014) at different points of time (Youmans et al., 2011; Tseng, et al., 2008). On the other hand, the factors that discourage fixation were discussed inherently within approaches or methods used to mitigate fixation. These factors include teamwork (Linsey et al., 2010) and facilitation (Cirlly et al., 2015), model making/physical prototyping (Youman et al., 2011), client expectation and the use of systematic design methods, both intuitive and logical (Crilly et al., 2015; Wood et al., 1999).

Different methods have been used to treat design fixation; some trying to categorize treatment methods based on the source of fixation and implementation method (Moreno et al, 2014) while others were based on the type of fixation (Youman et al., 2014). Broadly speaking, fixation caused by extrinsic factors was treated by providing defixation instructions (Christensen et al., 2007; Chrysikou & Weisberg, 2005), or through use of defixation materials in the form of abstract problem formulation (Zahner & Nickerson, 2010), use of partial pictorial stimulus (Cheng et al., 2014), verbal and /or visual analogy (Linsey et al., 2010; Viswanathan et al., 2013; Casakin & Goldschmidt, 1999).

Other researchers relied on having designers work in a full design environment to mitigate fixation by means of incorporating physical prototyping during the conceptualization phase (Youman et al., 2011), or through product dissection (Grantham et al., 2010). More methods such as the use of intuitive idea generation methods (Youman et al., 2014; Crilly et al., 2015), computer-assisted design (Dong & Sarkar, 2011), cognitive information feedback systems (Youman et al., 2005), interdisciplinary teams, and belief changing (Gordon et al., 1961) were also used. The intrinsic causes were managed through the use of incubation periods (Smith & Linsey, 2011), problem reformulation (Linsey et al., 2010; Zahner et al., 2010), timely warning (Luchins, 1942), and teamwork (Linsey et al., 2010; Crilly et al., 2015; Toh et al., 2012).

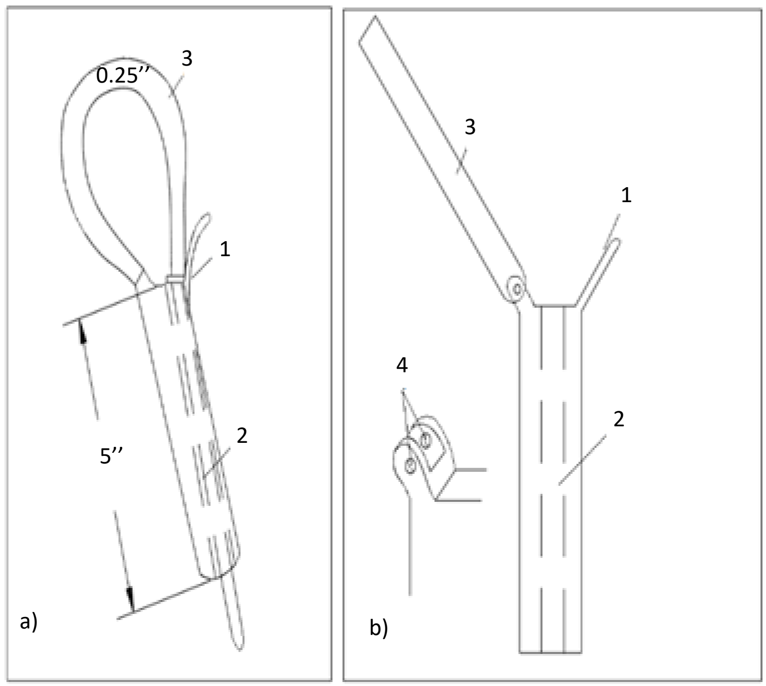

Fig.1 (a) Opener for Arthritis showing designer fixation on non-producible features, Part designed for AM, and (b) Same part modified for Conventional processes, mainly casting and machining.

Overall, researchers have extensively discussed design fixation in terms of its causes, mitigation methods and its effect on ideations. However, the fixation on non-producible features, their causes, and treatment methods were not discussed in the literature. A recent study by the authors found that designers who design for additive manufacturing fixated on non-producible features when asked to modify their design for ease of manufacturing using conventional processes (Abdelall, Frank, and Stone, 2018). An example where a designer was fixated on and created more non-producible features is shown in Figure 1. As shown, the designer tended to transfer and create extra non-producible features on their modified designs, such as internal sharp edges (modified design), thin wall sections (1), narrow and deep cavities (2), extremely long or flexible sections (3), tight tolerances, multiple components and materials (modified design), and new non-producible features (4). Fixation on the non-producible features is not desirable because it complicates the production process of the designs. Therefore, this research attempts to treat this type of fixation utilizing manufacturability analysis feedback from a prototype DFM software. The DFM software is used to assess the *machinability* of designs created during the conceptualization phase. The assessment results are provided as a 3D visual report to help designers during the modification process. Within the report, the design features appear in different colors representing their ease of manufacturing (from red to blue). To assess the effectiveness of the feedback of DFM software on mitigating fixation three main questions are posed; 1) *Does the use of DFM software while redesigning reduce fixation on non-producible features of original design?, 2) Does DFM software help designers to modify their design to be easier to manufacture (i.e., easier to machine)? and 3) Do designers who use DFM software experience less redesign difficulty and frustration while redesigning?*

Methods

In this study, two experimental conditions were used, a *Fixation* group and a *Defixation* group. Both groups were given design for manufacturability (DFM) training sessions. After training, both groups were asked to design a part where additive manufacturing would be the method of manufacture. The fixation group was asked to self-assess their own designs in terms of their ease of machining while the defixation group assessed their designs using DFM software. After assessment of designs, participants in both groups were asked to modify their previous designs to make them easier to manufacture using a conventional process, namely machining. Details of the DfM software, design problem, experimental groups, participants, procedures and dependent variables are provided below.

ANA- A Design for Manufacturability Based Software

ANA is an automated manufacturability analysis software developed to assist the designer in decision-making during the conceptual design phase. Unlike other manufacturability analysis tools, ANA runs the DfM analysis for a given design utilizing a feature-free algorithm where an STL file format of the part is used. ANA consists of four modules; machining, sand casting, die casting and welding. Depending on the chosen module, the manufacturability analysis is performed considering four metrics related to the chosen module to assess the manufacturability of the design. For example, machining ANA uses *visibility*, *reachability*, *accessibility*, and *setup complexity* to define the machinability of a given design. The ANA output is provided as a 3D visual report that includes both graphical and numerical results. The graphical results present design features in different colors representing their ease of manufacturing (from red to green). The numerical results include the individual numeric and normalized scores of each metric and aggregated score across the four metrics for a given process. In this paper, machining ANA was used to evaluate the machinability of designs created by participants, both original and modified. Details of machinability assessment through ANA are discussed below.

Machining ANA

The machinability of a part is defined in ANA as a combination of four metrics, visibility, reachability, accessibility, and setup complexity.

The *visibility* metric is defined by the percentage of surface area of the part within the cutting tool line of sight. The visibility score is normalized on a scale from (0-1), where a score closer to zero indicates less visible surface and a score closer to one indicates more visible surface. Based on the visibility analysis, the model surface is colored from red (less visible) to green (more visible) to indicate areas/features that have visibility problems. An example of ANA visibility output is shown in Figure 2a.

The *reachability* metric reflects the tool length needed to machine the surface of the part. Long tools are not desirable because they may be associated with slow feed rates, poor surface quality, and shorter tool life. ANA calculates the reachability score based on the depth of features from stock, which defines the required tool length. As in visibility, the reachability score is normalized on a scale from (0-1). The graphical reachability results are generated by color coding the model surface areas based on their depth. For instance, in the model shown in Figure 2b, the areas that are colored with red require a longer tool compared to green areas.

The *accessibility* metric can be linked to the cutting tool diameter and model geometry. Lack of tool accessibility can result in unmachinable surface or even collision problems. The accessibility score is calculated by the percentage of surface area of a part that can be machined using a given tool diameter. The accessibility score is normalized on a scale from (0-1). As in reachability, the graphical results color code the model surface areas based their accessibility score. As shown in Figure 2c, the areas that are colored in red represent regions that can only be contacted by exceedingly small tools. If, for example, a designer created a pocket with interior 90-degree corners, those corners are not accessible by a round tool of any diameter.

The setup complexity metric measures the number of setups required to machine a model. Increasing the number of setups will lead to higher machining cost and time. The number of setups is calculated by finding the set of the feasible axes and angles through which a part can be machined (a *set covering* problem). Then, the score is normalized on a scale from (0-1). The

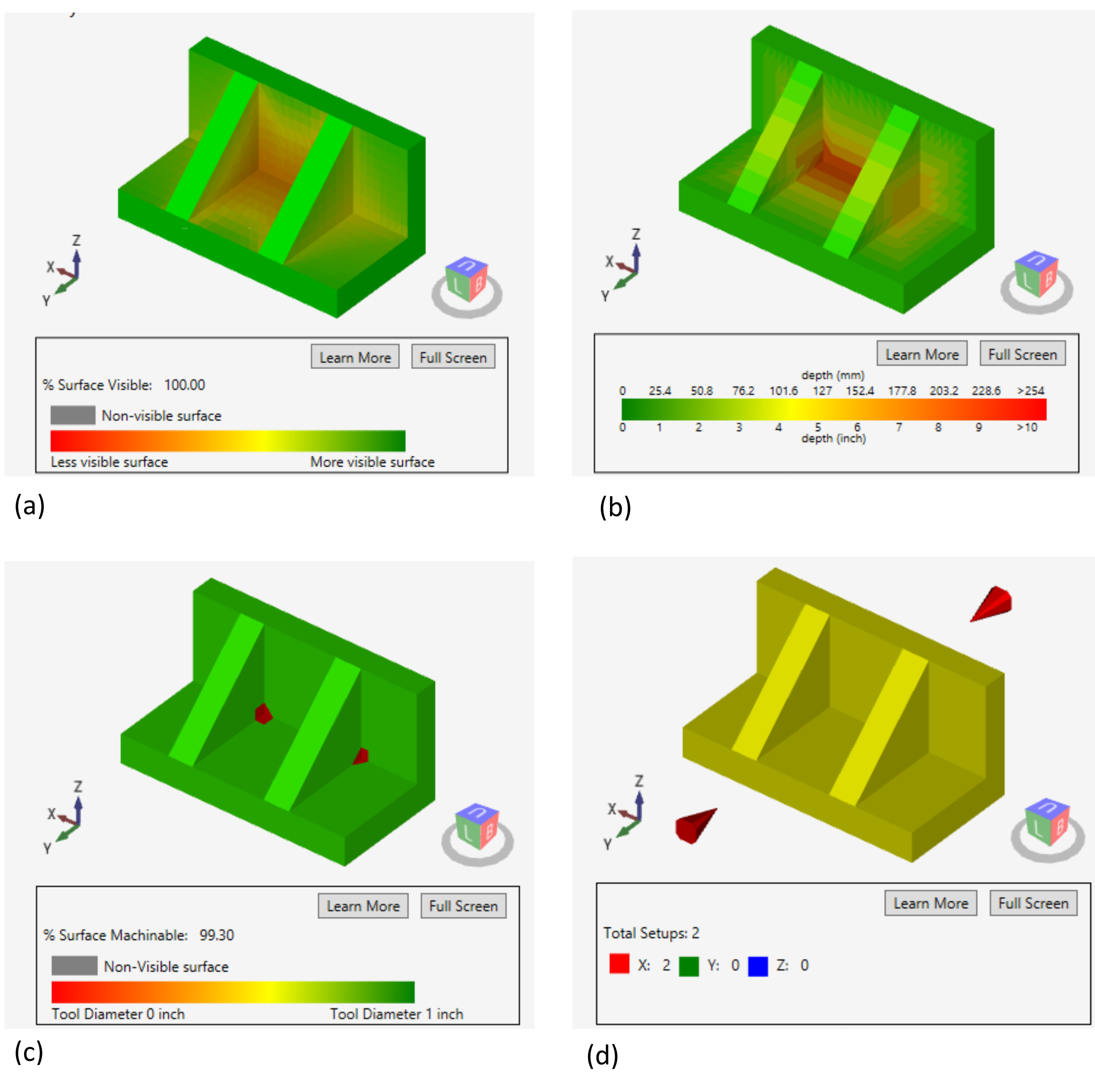

Fig.2 Example of ANA output (a) visibility, (b) reachability, (c) accessibility, and (d) setup complexity

graphical setup complexity results present the model and it is feasible setups orientations, as shown in Figure 2d.

The overall machinability score in ANA is calculated through weight averaging of the normalized scores for the previously discussed four metrics as in Equation 1.

$$Machinability = \sum_{i=1}^{4} W_i X_i \ , \ \sum_{i=1}^{4} W_i = 1 \quad (1)$$

Where X_i is the normalized score for the metric i, and W_i is the weight assigned for that metric (Hoefer, Chen & Frank., 2017).

In this study, ANA was used to provide DFM feedback and to evaluate the machinability of designs created by participants in two groups; a fixation group and a defixation group. The details of the groups will be discussed further in the experimental conditions section.

Design problem

Participants were given the design problem shown in Table 1, and asked to design a jar/can opener, according to the requirements and constraints listed in the design brief. An example of a commercially available opener is shown in Figure 3. In this study, the participants were asked to design an opener that will open jars, ring cans and pop bottles. The opener was chosen to open the numerous types in order to increase the complexity of the design problem and consequently the part design, making it more suitable for additive manufacturing.

Fig.3 Example of Jar Opener

The participants' familiarity with the design problem was assessed using a post experiment interview. Four participants (2 in each group) reported that they had previous exposure to the design problem. Those participants were asked about the degree of their exposure to this design problem, all of them were found to be partially exposed to the design problem. Their exposure was believed not to affect results because they were distributed among the two groups (Linsey, 2010).

Table 1 Design Brief

Customer: People with Arthritis
Problem statement: For people with arthritis in their hands or fingers, every day is a challenge. A simple daily task like putting on a seatbelt or opening a jar is a big problem. Opening a jar with hand grip or a can with an opener involves a twisting motion; which is considered painful or impossible for those with arthritis. The pain associated with the use of hand or fingers while opening is due to joint damage that causes functional disability. Statistics show that a person with arthritis has on average only 40% of normal power and pinch grip within six months of diagnosis, even with early commencement of medications. Therefore, an assistive device to substitute grip weakness and lack of hand strength to help in opening jars, bottles, and cans is required.
Design Statement: Design an opener that will allow Arthritis patients to open ring cans, pop bottles, jars and bottles easily with no pain.
Design Criteria/requirements: 1) Should open ring cans, plastic bottles, pop bottles and jars, 2) Should open different jar and bottle sizes within the range specified in the constraints, 3) Safe opening; it should grip the lid/cap securely without slipping while opening.
Constraints: 1) Should be a single component, 2) Should open a jar with lid diameters ranging from 1.5in - 4.5in, 3) Should open a bottle with lid diameters ranging from 1in - 2in, 4) Should fit people with different grip size, ranging from 4in - 6in, 5) Final design should fit in a bounding box of 10in x 5in x 2.5in.
Deliverables: Hand sketches, 3D CAD models and descriptions/comments

Experiment Conditions

Fixation Group

Participants in the fixation group were given the design brief and asked to generate as many ideas as they can. Meanwhile, they were encouraged to write any comments or descriptions on sketches to communicate their ideas. After that, they were asked to transfer their ideas to 3D models using SolidWorks software. After modeling, they were asked to self-assess the manufacturability of their design. Then, they were asked to modify their designs and make them easier to machine.

Defixation Group

Participants in the defixation group were given the same design brief and asked to do the same task as the fixation group with one difference; they were asked to assess the manufacturability of their designs using the DFM software (ANA). Then, they were asked to modify their design based on software feedback and make them easier to machine.

Hypotheses

In this study, each research question was associated with one hypothesis, shown below, to investigate the effect of DFM software feedback on mitigating design fixation on non-producible features;

Hypothesis1: Designers who utilize the DFM software to assess their designs will fixate less on non-producible features when redesigning for conventional manufacturing than those who self-assess their designs. As such, designers who utilize the DFM software feedback will fixate with less percentage than those who relied on their self-assessment.

Hypothesis2: For designers who utilize the feedback of DFM software, their modified deigns will be easier to manufacture than their original ones. Also, the percentage of change in the machinability of their designs will be higher than those who rely on their self-assessment.

Hypothesis3: Designers who utilize the feedback of DFM software will be less frustrated and will experience less redesign difficulty than those who rely on their self-assessment.

Participants

Thirty-two engineering students (four females, and twenty-eight male) with ages ranging from 18-35 participated in this experiment. Twenty-one participants (12 in the defixation group, and 9 from the fixation group) stated that they had previous experience with Design for Manufacturability (DFM), whereas twenty participants (nine in the control group and eleven in the defixation group) were found to have previous knowledge/training experience with Design for Additive Manufacturing (DFAM). Also, the majority of the participants indicated that they had previous design experience, except three in the defixation group. Most of them reported that they like designing things, with the exception of two (one in each group). Participants were asked to assess their modeling skills with SolidWorks on a scale from 1-10. Subjects in the fixation group were found to have a modeling skill level of 6.53 (1.13) compared to 6.38 (0.81) for those in the defixation group.

Procedure

The experiment was conducted in a closed lab room with a maximum of one subject per session. First, the participants were informed of the experiment's purpose and procedure and then read and signed a consent form and filled out a demographic survey. After that, participants were assigned to one of the experiment conditions, resulting in sixteen participants per condition. This was followed by giving them a DFM training session, wherein, they were educated about DFM approaches, goals, guidelines, general design rules/restrictions considered when designing for conventional processes. The training was supported by images of what should be and not be done when considering conventional processes as manufacturing process while designing. At the end of DFM training, participants in each group were educated about Additive Manufacturing (AM) and the advantage it provides to the designer in terms of design freedom to create highly complex designs. The AM training was supported by images of complex parts produced by AM.

Then, participants were asked to read the design brief/problem. Meanwhile, they were shown images of the different cans, jars and bottles they will be designing the opener for, as mentioned in the design brief. Next, the researcher explained the design problem verbally once again to ensure their understanding, wherein, their attention was drawn toward satisfying the design requirements and constraints listed within the design brief. After that, they were given plain paper and asked to generate as many ideas as they can, given that their part will be manufactured by AM.

Participants were asked to comment and write descriptions to clarify and communicate their ideas/sketches.

Once the idea generation task ended, participants were asked to transfer their favorite idea to a 3D model using SolidWorks. After the modeling session, they were asked to imagine that their designs succeeded, and demand rose to mass quantities. Based on that, participants in the fixation group were asked to self-assess and modify their previous design using hand sketches to make it easily manufactured with conventional processes. In contrast, those in the defixation group were allowed to use the DFM software (Figure 4) to assess the manufacturability of their design, then they were told to modify their designs using hand sketches for ease of manufacturing utilizing the DFM software feedback. Then, all participants were asked to apply modifications to their 3D models. The experiments ended with an interview.

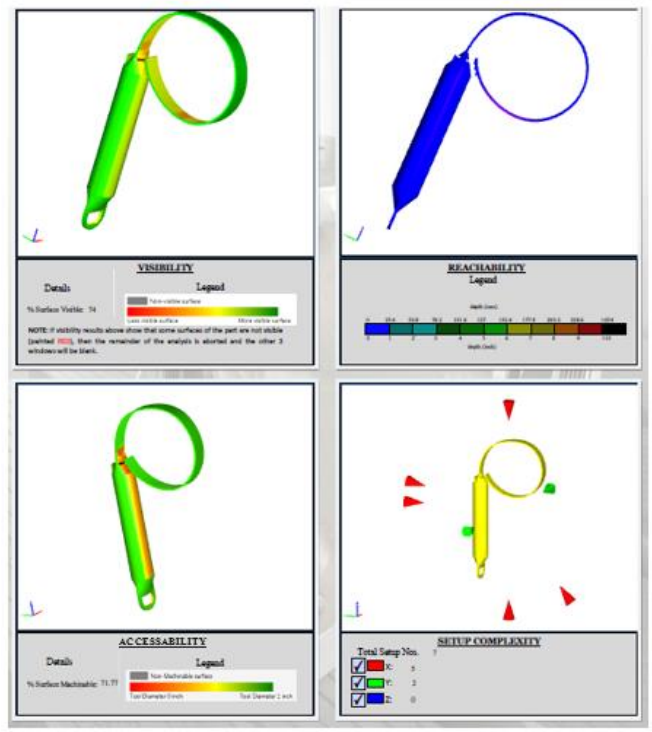

Fig.4 Sample of DFM software 3D visual feedback

Dependent Variables

To evaluate the effect of DFM software feedback on mitigating designer fixation on non-producible features, different dependent variables were used (Table 2). These variables were design fixation, machinability of designs and designer experience.

Table 2 Dependent variables and associated metrics

	Dependent variable	Metric
Hypothesis 1	Design Fixation	Number of non-producible features generated in modified design concepts Fixation percentage
Hypothesis 2	Manufacturability of designs	Machinability of original design Machinability of modified design Percentage of change in machinability
Hypothesis 3	Designer experience	Frustration score
		Redesign Difficulty score

*Design Fixation***.** Design fixation was measured by the mean number of non-producible features transferred /generated by the designer to redesigned concepts and the fixation percentage.

The mean number of non-producible features was obtained by assessing each design based on the presence of a set of non-producible features in initial and modified designs. Then, the mean number of non-producible features in both the fixation and defixation groups were compared to assess the effect of DFM software on reducing the number of non-producible feature transfers.

Fixation percentage was calculated by dividing the number of transferred features by the total number of previous features. This metric was used to determine which group experienced more fixation (Moreno et al., 2015). Two judges were consulted and Pearson correlation tests of the judges' scores indicated a strong consistency between raters (r=0.93).

*Manufacturability of Design*s. The manufacturability score of designs, mainly machinability score, measured how easy to machine the design. The DFM software (ANA) was used to obtain machinability score for designs. To validate the software scoring, two judges were consulted and Pearson correlation tests of the judges' scores indicated a strong consistency between scores (r=0.91).

*Designer Experience***.** The designer experience was evaluated by two metrics; degree of designer frustration and redesign difficulty. Both frustration and redesign difficulty were measured using a Likert scale during the post experiment interview. All participants were asked to rate their frustration degree, if any, and to specify when and why they felt frustrated. In addition, they were asked to rate the degree of redesign difficulty. The difficulty of redesign was further investigated by asking them whether they thought that considering AM as a manufacturing process while designing initially made it harder or easier to redesign/modify parts for ease of manufacturing later. Also, they were asked whether they found it hard/easy to apply the skills they learned and to specify which skill they would prefer to use in the future and the reasons for that. In the defixation group, the effect of DFM software feedback on facilitating redesign was further investigated by asking them using a Likert scale whether they found the feedback helpful or not in redesigning their parts for ease of manufacturing later.

Results

Design Fixation

Mean number of non-producible features

To understand whether the DFM based - 3D visual feedback affected fixation on non-producible features, a paired t-test for the mean number of non-producible features for both first

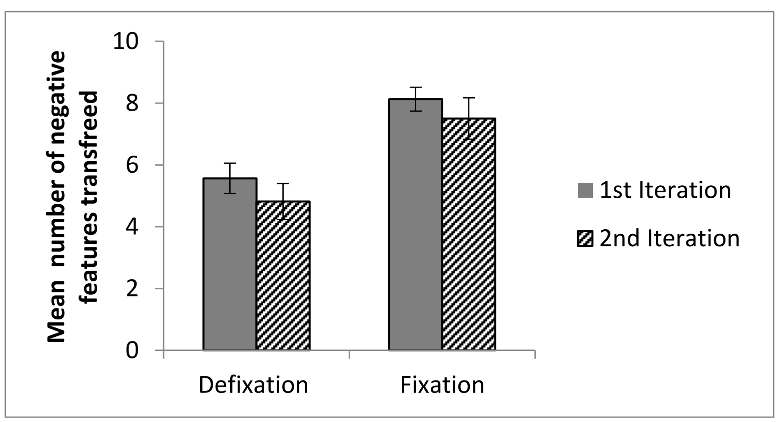

Fig.5 Mean number of non-producible features in designs created by both groups during first and second design iteration. Error bar represents ±1 standard error.

and second design iteration of the defixation group was implemented. The results showed that the mean number of non-producible features between first and second design iteration differ significantly t (2, 16) =3.00, p= 0.009 (Figure 5).

As expected, Wisxlcon test showed that the mean number of non-producible features did not differ between first and second design iterations (W=40, p=0.107, one tailed).

Fixation Percentage

Furthermore, a t-test of fixation percentage on non-producible features between the fixation and defixation groups revealed that the defixation group fixated significantly less on non-producible features compared to the fixation group (t (1, 29)=2.99, p=0.003, one tailed), as shown in Figure 6.

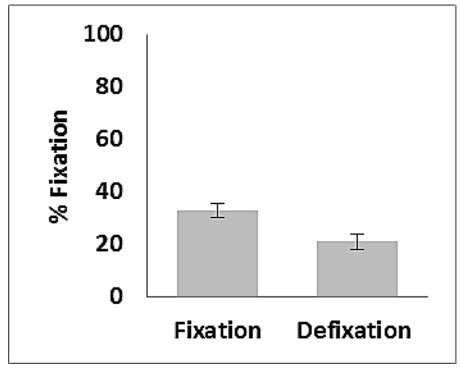

Fig.6 Fixation percentage on non-producible features for both groups. Error bar represents ±1 standard error.

Manufacturability

Machinability Score

ANA software was used to obtain machinability scores for the designs in both groups. Then, Wilcoxon-Mann Whitney testing was used to understand the effect of the type of feedback on machinability within each group. The results indicated that the feedback of the DFM software helped the participants in the defixation group to significantly improve the machinability of their designs during second iteration (W=64.5, p=0.025, one tailed test). In comparison, there was no significant difference in the machinability of the first and second designs for the fixation group, (W=33.0, p=0.52, one tailed test), as shown in Figure 7.

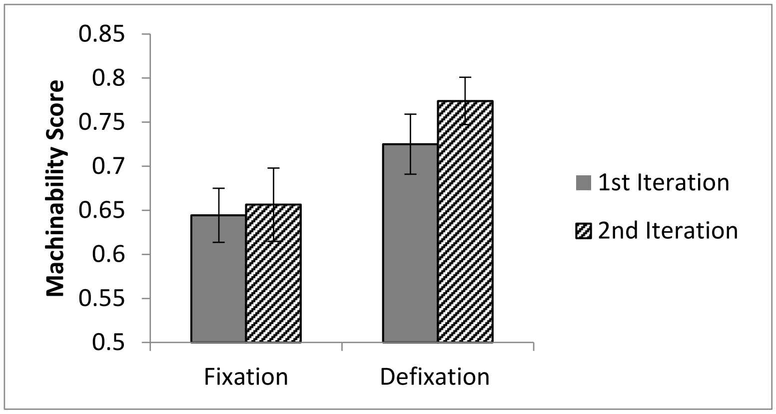

Fig.7 Average ANA machinability score of designs created by both groups during first and second design iteration. Error bar represents ±1 standard error.

More, Mann Whitney test showed that the percentage of change in machinability scores for the defixation group were significantly higher than the control group, ($U= 71$, $p=0.045$, two tailed tests). This indicates that the feedback of the DFM software helped the participants in the defixation group to improve machinability of their designs compared to defixation group.

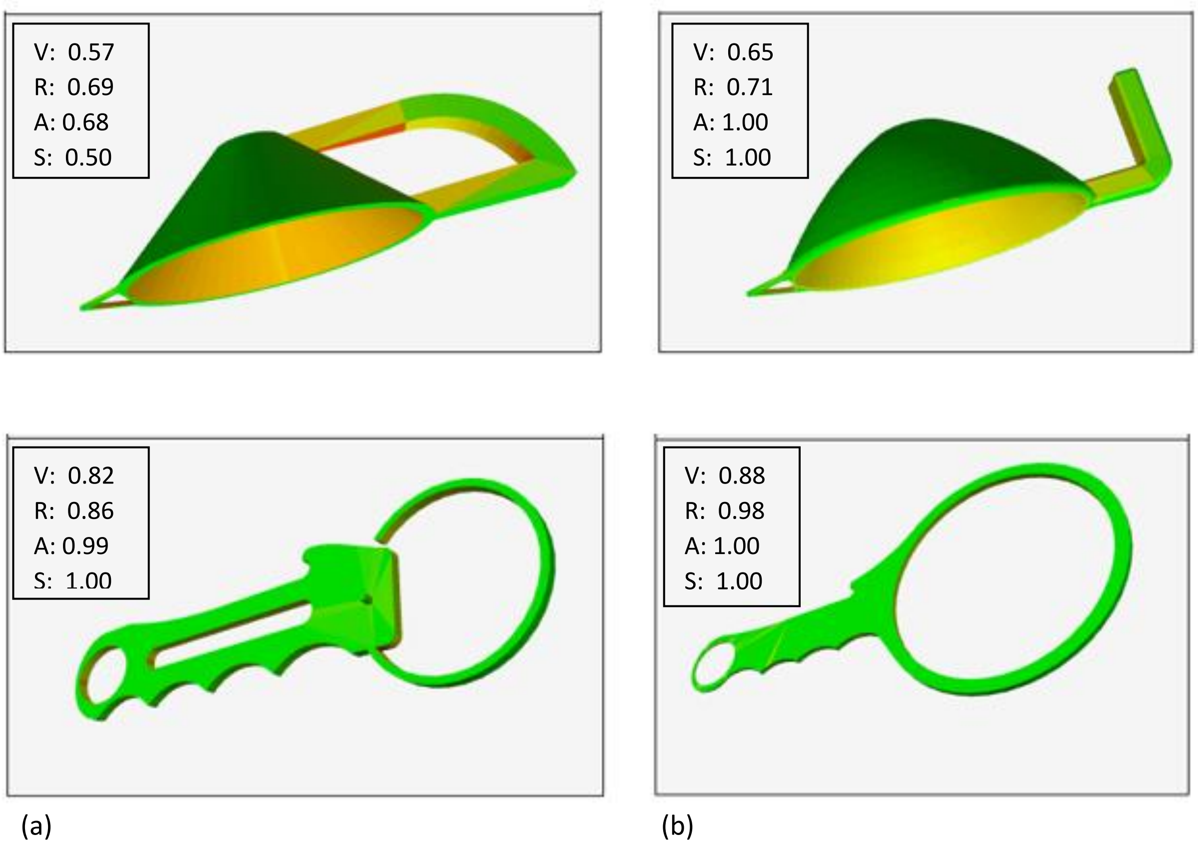

Fig.8 Sample of designs created by the defixation group; (a) first design iteration, (b) second design iteration.
*V: Visibility score, R: Reachability score, a: Accessibility score, and S: Setup complexity score

Samples of the first and second design iteration machining analysis results for the defixation group are shown in Figure 8. As shown in Figure 8, participants were able to improve the machinability of their designs with the aid of ANA feedback. For example, the first design iteration (Figure 8a) contains areas of possible machinability problems such as internal sharp corners and improper spacing for cutting tool access. Such features are not desirable because they are less visible, less reachable, and less accessible and consequently require more setups in order to be created. After use of ANA feedback (Figure 8a), the machinability of second design iteration (Figure 8b) was improved. The internal sharp corners were either replaced by round ones (cup shape design) or eliminated (wrench shape design). Additionally, proper spacing was provided for the cutting tool to avoid collision problems or unmachinable areas. In the new design, a less constrained space was obtained in the cup shape design through having an open-end handle. In the wrench shape design, a larger diameter hole combined with eliminating slot feature were used to avoid tool spacing problem. Also, increasing part symmetry (wrench shape design) simplified the design further, leading to better machinability. Overall, ANA seemed to help participants improve their designs overall; however, some features like thin walls still existed.

Designer Experience

Redesign Difficulty

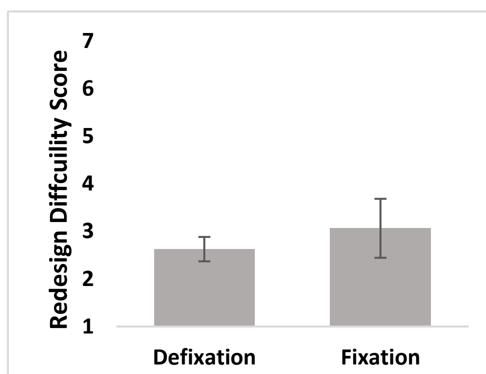

Fig. 9 Average redesign difficulty score for both groups. Error bar represents ±1 standard error.

The effect of feedback type on designer experience in term of the redesign difficulty was assessed using Mann-Whitney testing. The analysis results showed that there was no difference in redesign difficulty scores between groups (U=104, p=0. 19, one tailed). As shown in Figure

9, the defixation group had a redesign difficulty score of 2.63 (0.26) on average compared to 3.06 (1.24) for the fixation group.

It is worth mentioning that interview results indicated that 75% of the defixation group participants found the DFM software feedback moderately helpful during the redesign process, 19% of them found the feedback strongly helpful, and 6% found the feedback slightly helpful.

Frustration

The effect of feedback type on designer frustration between the fixation and defixation group was examined. Mann-Whitney test results showed that designer frustration did not differ between groups ($U=103$, $p=0.18$, one tailed), as shown in Figure 10. The interview results showed that modeling and ideation were the main reasons for frustrations in both groups.

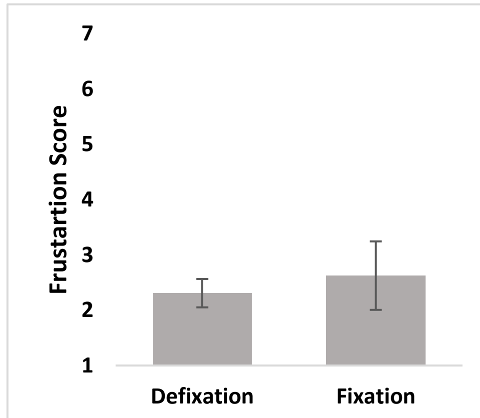

Fig.10 Average frustration score for both groups. Error bar represents ±1 standard error.

Discussion

Research question 1: Does the use of DFM software while redesigning reduce fixation on non-producible features of original design?

Recent studies by the authors showed that designers who design for AM experience a fixation on non-producible features when asked to redesign for conventional manufacturing, in light of their self-assessment of designs. This work focused on investigating the fixation on non-producible features and possible treatment method through the use of 3D visual feedback. It was found that designers who relied on their self-assessment while modifying designs showed evidence of fixation, where they fixated on non-producible features of the original designs and transferred them to their modified designs. In contrast, there was no evidence of fixation among the defixation group. To support that, it was hypothesized that a designer who utilized the 3D visual feedback will experience less fixation percentage compared to those who relied on self-assessment feedback. This hypothesis was supported, wherein results showed that participants who used the 3D visual feedback had less fixation percentage on non-producible features than those who relied on self-assessment.

One possible explanation is that the 3D visual feedback improved the designer's ability of detecting non-producible features. As such, it may reduce the mental demand of the designers to recall DFM restrictions and knowledge while modifying designs, and consequently providing more attention and time to detect and eliminate fixation (Youman, 2011; Crilly, 2015). In particular, the DFM based software provided an immediate feedback that critiques, evaluates, detects, and subsequently eases detachment from unacceptable (non-producible) features. This was further supported by participant's responses to a question about whether they found the visual feedback helpful, where they reported that the visual feedback showed exactly where the problem in their design was. Similarly, the *absence* of visual aid combined with *recency* of AM knowledge (Abdelall, Frank, and Stone, 2017) for the fixation group increase the cognitive demands and the distraction effect in memory to retrieve DFM knowledge and detect non-producible features simultaneously, causing fixation.

Research Question 2:

Does DFM software help designers to modify their design to be easier to manufacture (i.e., easier to machine)?

As hypothesized, it was found that the percentage of change in the machinability of designs for the fixation group were significantly lower than that for the defixation group. Also, the machinability of the first and second iteration designs of the fixation group did not differ, in other words, the designers failed to make their designs easier to machine in light of their self-assessment. In comparison, the machinability of second iteration designs for the defixation group were significantly higher than those of the first iteration. Thus, the DFM based software helped designers improve machinability by means of detecting problematic features and regions in their designs and present them in 3D visual format. As discussed earlier, the ability of 3D visual feedback to detect and display non-producible features lowered the mental demand of the designers and triggered memories related to DFM knowledge while modifying designs. In other words, the designers have more time to retrieve DFM knowledge and think of ways to resolve negative features problems, facilitating detachment from non-producible features and improving machinability of designs. As such, the failure of fixation group designers in improving machinability of their second iteration can be explained. They spent more time trying to detect and understand problems in their designs, which means less time to retrieve knowledge, reasoning and finding solutions to resolve non-producible feature problems.

Research Question 3:

Do designers who use DFM software while redesigning experience less redesign difficulty and frustration?

It was hypothesized that the designers who rely on the DFM software feedback will experience lower redesign difficulty and frustration than those who do not. The statistical analysis results failed to support this hypothesis, where it was found that the redesign difficulty and frustration did not differ between groups. However, the interview response indicated that with regard to re-design difficulty, 88% of the fixation group indicated that designing for AM made it harder to modify their design later for conventional processes compared to 56% of those who used the visual feedback, giving an indication that the fixation group experienced more difficulty while redesigning compared to defixation group. The difficulty of redesign can justify the preference of 36% of fixation group to use DFAM principles while designing in the future compared to 50% of the DFM software group, indicating that the 3D visual feedback encourages them to use DFAM and might make them less worried of failure when switching back to conventional processes. As stated earlier, this could be related to the fact that the visual feedback will act as a direct reminder of non-producible features and hence facilitate detection and elimination of undesirable features leading to better modification of original ideas.

Conclusion

A recent study by the authors showed that designing for AM had a negative long-term effect on the designer's skill of creating conventionally manufactured parts, due to a problem called design fixation. Therefore, this study aimed to understand the effectiveness of using 3D visual feedback from DFM software on mitigating the design fixation on the non-producible features. Results showed that the feedback of the DFM software reduces design fixation, as it reduced the number of non-producible features transferred to the modified designs. Also, the machinability of the modified designs were better in the case of using the 3D visual feedback compared to those who self-assess their designs. The study results suggest that the 3D visual feedback of the DFM software is a possible solution for mitigating design fixation. Moreover, this study supports the role of the DFM software in facilitating migration of designs from additive manufacturing to conventional manufacturing, which would be a benefit to industry if a design is ramped up to mass production. This study focused on the non-producible features and the manufacturability of designs in a machining process only. It is hoped that one can generalize the results to other conventional manufacturing processes in future work.

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A METHOD TO MIGRATE COMPONENT DESIGNS BETWEEN ADDITIVE AND CONVENTIONAL MANUFACTURING

Esraa S. Abdelall & Matthew C. Frank

Abstract

This paper presents a new method to help designers migrate their designs from additive manufacturing (AM) to conventional manufacturing, in particular, migrating a design with multiple undercuts from additive manufacturing to a machinable set of subcomponents. The method provides the automated dissection of a design into pieces such that the surface of undercuts become more visible, reachable and machinable. The machinability of the resulting pieces is used to evaluate the efficiency of the solution. Results showed that the method can dissect designs into pieces that have better machinability on average than the original design. The findings of this study should be of interest to designers and manufacturing engineers working to create and improve new products.

Keywords

Additive Manufacturing, Design Migration

Introduction

The need for innovative designs that are both high performing and economical often lead designers to increasing design complexity of their models. For example, automotive components with high specific strength and low-cost are might only be achieved through adding more features that can complicate the part design. As design complexity increases, the manufacturability of the design may decrease due to the addition of features such as undercuts or captured cavities (Figure 1).

These features are considered difficult or impossible to manufacture using conventional processes due to a typical tools' accessibility, visibility, and/or reachability problems. Therefore, a more advanced manufacturing process such as Additive Manufacturing (AM) might be required to produce these features.

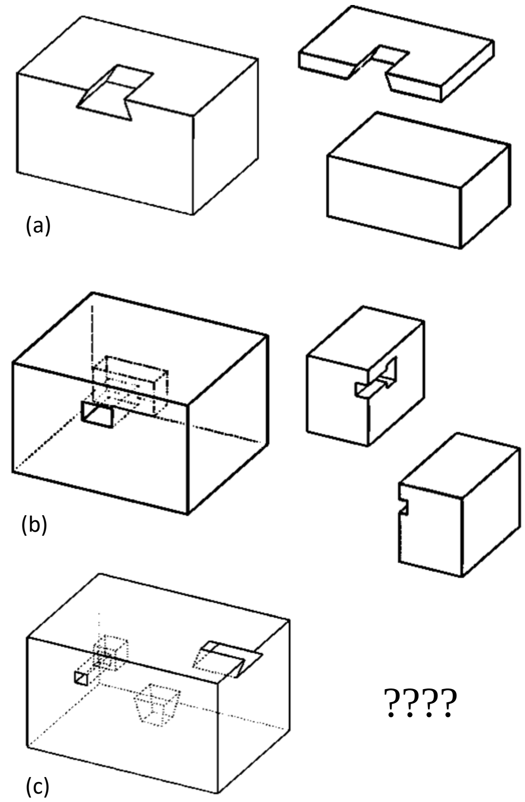


Fig.1 Example of parts with non-producible features

AM processes are capable of producing parts with some of the aforementioned problem features because it is a tool-less and layer-based process. However, these processes are often limited with respect to materials choices, production volume and meeting functionality requirements. A challenge might arise if a part designed for AM, and perhaps low volume production, needs to shift back to a conventional process. In fact, it can be argued that parts more often migrate from a conventional production process to AM; not usually the other direction. Interestingly, a recent study by the authors showed that the migration of designs from AM to a conventional process is not an easy task. Wherein, it was found that designers fixated on the non-producible features such as undercuts when asked to modify their AM designs to make them suitable for a process like machining. One reason that justified fixation is the sheer existence of many non-producible features in AM designs which complicate a designer's job of capturing and modifying these features. In other words, if the part has only one non-producible feature, (Figure1a, b) then the problem of migrating designs may no longer exist. Such parts (Figure1a, b) can be dissected into two pieces that can be either CNC machined or even AM-produced without sacrificial supports. In contrast, having multiple non-producible features (Figure1c) will complicate the sectioning line(s) determination and therefore make design migration difficult. With multiple features, the designers have to consider the number, location, orientation and size of features to define sectioning lines. Therefore, there is a need to develop a method that will allow automatic determination of sectioning lines to facilitate the conversion of designs from AM to Conventional processes.

Related Work

In literature, different designs strategies and methods have been developed to help designers build and modify designs for low cost conventional manufacturing. One of the oldest methods is the Boothroyd and Dewhurst (1983) Design for Manufacturing (DFM) method. Boothroyd and Dewhurst' DFM method is a set of guidelines that help make designs easier to manufacture with conventional processes. These guidelines are manually used with a set of worksheets to help designers modify and/or decompose their parts into simpler and easier to manufacture components that can be assembled later to build a more complex design. The Boothroyd-Dewhurst DFM tool provides detailed information related to design manufacturability time and cost in tabular format or 2D charts.

Later, researchers developed tools that can automatically locate the features or areas in a design that need modifications. These tools analyze designs given a specific manufacturing process and provide feedback in the form of warnings when features violate a set of predefined constraints (Tenenbaum & Cutkosky, 1992), or as a ranking for manufacturability of design features where features with lower scores are possible candidates for redesign (Yannoulakis, Joshi, & Wysk, 1994; Warnecke & Bassler, 1988). Other tools relied on performing complex manufacturability analysis of a design based on a predefined set of capabilities given a certain manufacturing process and provided results in textual format (Madan, Rao & Kundra, 2007; Lockett, 2005; Ravi, 2003; Er & Dias, 2000) or as 3D colored feedback within the CAD system (Geometric, 2009; DFMA, 2015; Cast Designer, 2015), or as a portable 3D color coded PDF (Traband, 2013; Hoefer, Chen & Frank., 2017). Overall, these tools were tailored based on their designers' requirements (Satyandra, Das & Nau, 1997) and in light of given manufacturing processes, mainly casting and machining. Therefore, the efficiency of these tools in facilitating design modifications depend largely on the quality and comprehensiveness of the feedback and the ability of the designers to interpret it.

On the other hand, some researchers built process selection interfaces to help designers select the best process for manufacturing their designs. In these interfaces, the design is usually assessed against a set of manufacturing processes including both conventional and AM processes. Different decision-making tools such as Multicriteria decision making (MCDM) (Masood & Soo, 2002), Analytical Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOSIS) (Byun& Lee, 2005; Panda1, Bibhuti & Deepak, 2014) and Fuzzy-AHP (Akarte, Ravi & Creese, 1999; Munguian et al., 2010; Er & Dias, 2000) were used for assessment in these interfaces. These interfaces presented results as ranking of the manufacturing process, where the manufacturing process with the higher score represents the more favorable process for producing a design. Although the process selection interfaces can be used to determine which process is easier to convert the design to, it provides no indication on how to modify designs for that purpose.

Overall, currently available methods are a combination of manufacturability assessment and/or process selection. These methods are usually process specific, some of them have a difficulty of knowledge gathering, coding and updating and the rest are based on evaluating a design using common decision-making methods to select manufacturing process. These methods lack direct design suggestions and automatic modifications, and none of them work as migration tools from AM to conventional processes. Therefore, there is a need to develop a method that will allow designs to migrate from AM to conventional processes. Although a migration method covering different conventional processes is required, the scope of this paper will be limited to developing a method that will allow bidirectional conversion of designs from AM to machining.

Methodology

Problem Statement

This study proposes a method that allows migration of a design from AM to conventional processes. The design conversion from one manufacturing process to another requires a designer to reconsider the capabilities and limitations of the new processes while modifying their design. For example, undercuts are a common feature that is hard to create using conventional processes, but it is not as much of a challenge at all for Additive manufacturing. This paper proposes a migration method that focuses on solving the undercut machinability problem when the production process changes from AM to machining. The solution will provide a suggestion for separating the part into subcomponents to increase visibility, reachability, accessibility and consequently machinability of these undercut features. Details of the proposed methods are presented in the following section.

Overview of Solution Method

To machine an undercut, the visibility of its surfaces must increase. To do so, the proposed method suggests part sectioning into subcomponents such that all surfaces of the undercut became more visible and reachable from enough directions. The method is illustrated in Figure 2. In the first step (Figure 2a), an STL file of the CAD model should be prepared, then a machinability analysis of the file is performed in a design for manufacturability-based software called ANA. The non-machinable areas in the model are identified in ANA. Next, the points associated with these areas are extracted. After that, the midpoint for the bounding box of each feature will be calculated and stored. The midpoints are then used for defining the parting line. Once the parting line is determined, the parting surface is obtained by extruding the cutting line along a line that is

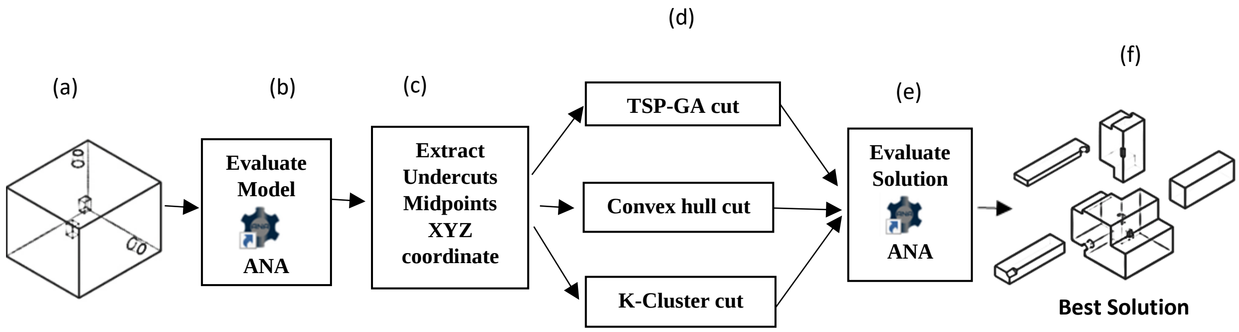


Fig.2 Overview of solution method; (a) model input, (b) DfM analysis, (c) non-producible feature identification, (d) dissection methods, (e) re-analyze manufacturability, and (f) resultant part set

perpendicular to the cut line. After dissection, the quality of the solution is evaluated by testing subcomponents in ANA to check their machinability. The details for each phase of method for are presented below.

Determination of undercuts mid points

In the proposed method, each undercut feature can be represented by a point. The points are determined by calculating the midpoint for the bounding box of that feature. To find a bounding box, the non-machinable areas are first identified in ANA. Then, the points associated with these areas are extracted. After that, the bounding box for each feature will be calculated and then the midpoint for each bounding box will be stored. Once these points are identified the process of finding cut lines will begin.

Determination of feasible parting line

In the proposed method, the cut line is formed by considering mid points for the features. Three possible approaches can be used to define cut line(s); details of each approach are presented below.

First Approach: TSP-GA cut

```
% Generate initial population
Read undercuts_ locations, undercuts_number
For i=1 to undercuts_number
 Undercuts_location(i)=Starting_node
 Find Shortest path(i)
 Result(i)= Shortest path(i)
End
Initial_ population= Result
% Apply GA to find best solution
 While k<= Maxiteration & Bestfitness<max fitness
   Do
     Fitness calculation
     Selection
     Crossover
     Mutation
 End while
Return best solution
```

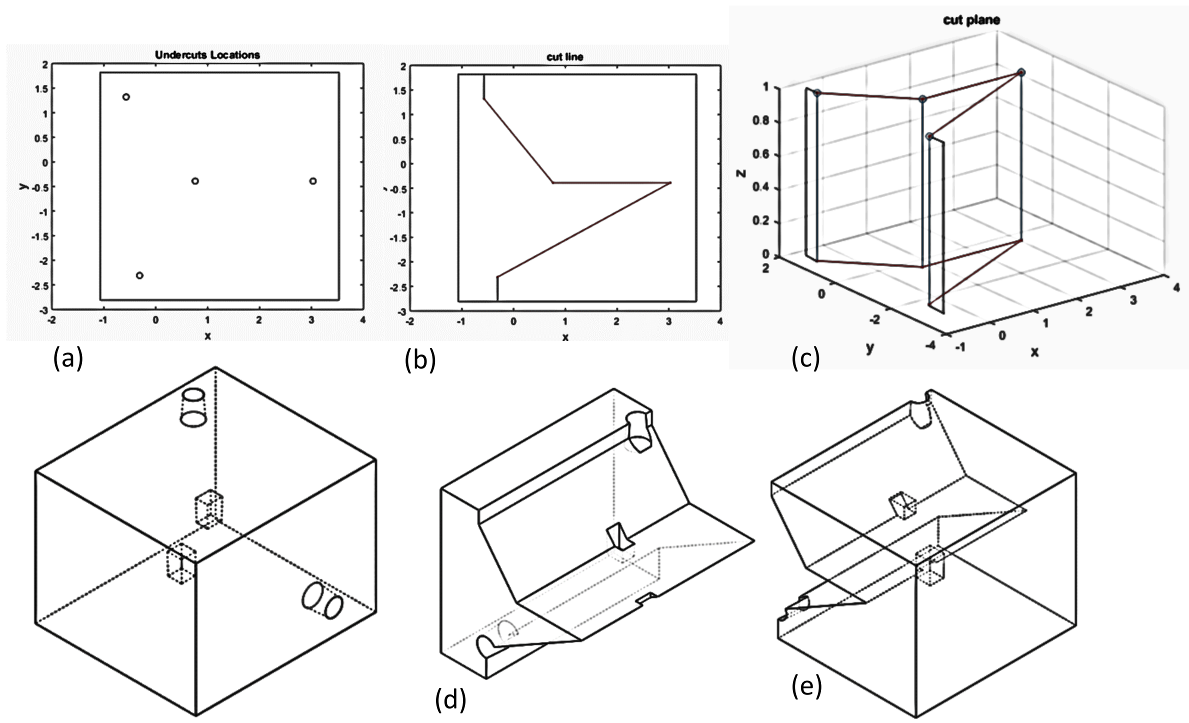
Fig.3 Pseudo code for TSP-GA cut method

In this approach, the determination of parting line problem can be formulated as a Traveling Salesman Problem (TSP). Wherein, the features' mid points are first projected to the XY plane, and then a genetic algorithm (GA) is used to solve the associated TSP. The traveling salesman problem is an old problem that aims to find the shortest distance path/tour linking a set of vertices given that each vertex will be visited exactly once and then return to the starting vertex. The TSP can be represented as a graph having a set of vertices and a set of edges between vertices with a goal of reducing the cost of travel between all vertices. The cost function is defined by calculating the distance between vertices given one vertex chosen randomly to be the start node. Different paths can be obtained when changing starting nodes, therefore, the genetic algorithm is used to find the best path that will result in lower travel cost. GA is usually used for solving maximization problems, therefore, the fitness function for the GA will be the inverse for the objective function for the TSP (Dwivedi et al.,2012), as follows:

TSP Objective Function= Min (Tour cost)

GA fitness function = Max (1/Tour cost)

For defining the cut line, all midpoints of the undercuts are first projected on the XY-plane to form vertices for the TSP (Figure.4a). Then, TSP-GA is used to connect these points, resulting in one cut line dividing the part into two subcomponents only (Figure.4b). The complexity of the parting line varies depending on the number and location of undercuts. The cut plane is defined by extruding the cut line along one line that is perpendicular to the cut line through the entire part depth (Figure 4c).



ANA Results	V	R	A	SC	#S	#P
Original	0.81	0.85	0.73	0.06	11	1
TSP-GA Cut	0.80	0.91	0.69	0.67	4	2

Fig.4 Dissecting part using TSP -GA method; (a) undercuts locations, (b) Cut line, (c) Cut plane (d) and (e) dissected pieces. V: Visibility, R: Reachability, A: Accessibility, SC: Setup complexity, #S: # of setups, #P: # of pieces

Although this approach will dissect a part into two unique subcomponents that can fit in one place and can be self-fixtured during assembly, the cut lines' complexity can result in many joining issues. For example, the subcomponent in Figure 4 can be assembled only from one direction which lessens the freedom to join pieces, complicating the joining process. In case of welding these subcomponents, the weld joints' location will be almost inaccessible. The operator will be welding in constrained spaces, resulting in poor weldments. Constrained welding can also create many problems, especially when welding ductile material where there will be no adequate access and space for depositing the weld metal. On the other hand, the contact surfaces are critical for optimum welding. Flat contact surfaces located in accessible areas of part and at appropriate distance from part' features are usually favorable to facilitate addition energy director features (i.e. small triangular raised bead) for good quality welding (Gillespie, 1988). Flat surfaces are also preferable for gripping pieces in the work holding devices for machining because it will ensure that pieces are sufficiently rigid to withstand machining forces in addition to providing a good reference (datum) for machined features (Boothroyd & Dewhurst, 1998). Depending on complexity of the cut line, this approach may not result in good flat contact surfaces.

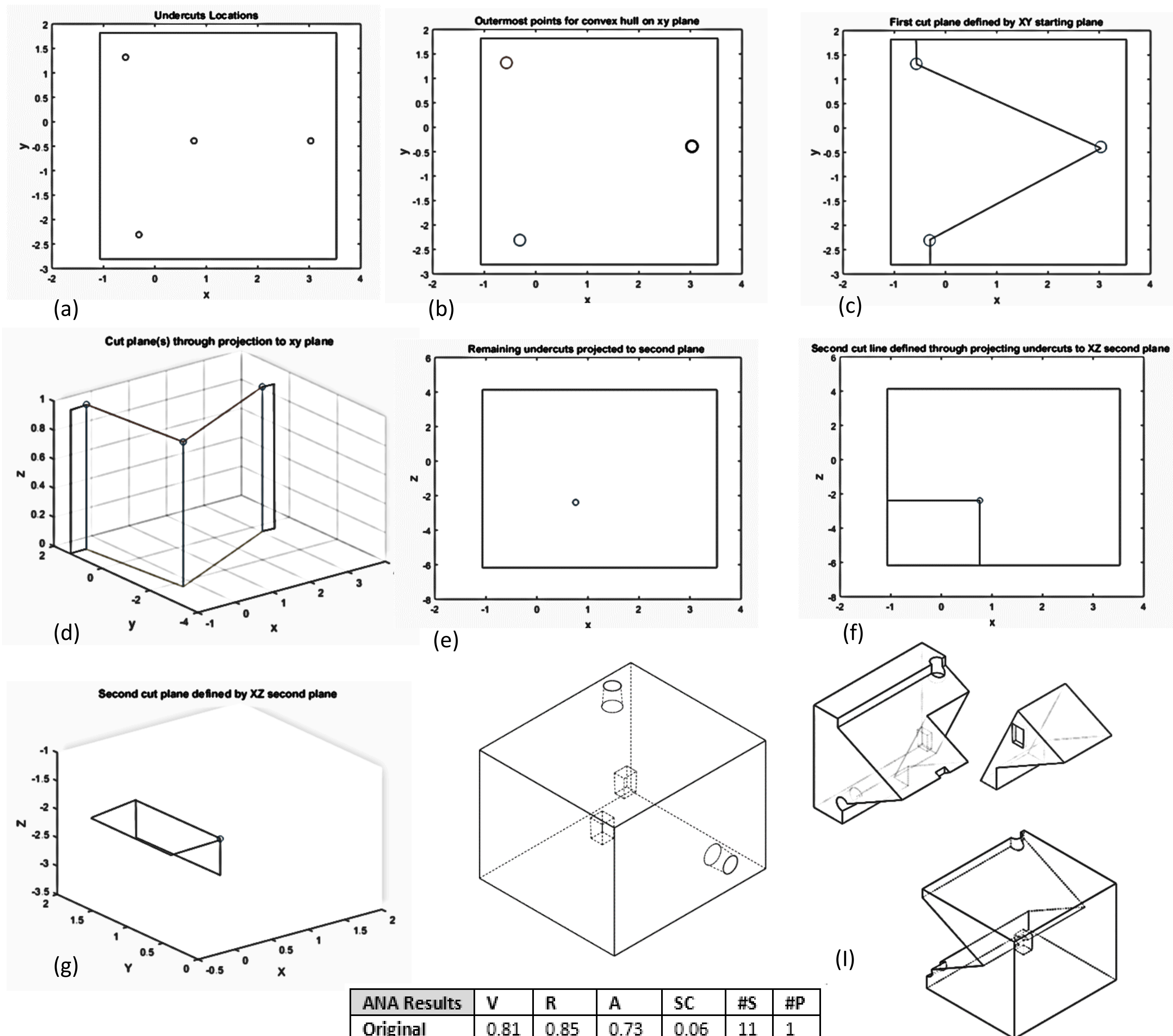
Second Approach: Convex hull Cut

The Convex hull-cut approach relies on classifying points based on their convexity on the XY, XZ, and YZ planes to define cut lines. The cut lines defined using this method are expected to be simpler compared to that of the previous approach. As in the previous approach, a unique solution will be obtained using this method where the part will be dissected into pieces each having a unique position to occupy (Figure 6i). The algorithms through which the solution can be obtained are presented in Figure 5.

```
Get XYZ_vertices
Project vertices on XY, XZ, YZ
% starting plane
Find Convexhull [XYvertices, XZvertices, YZvertices]
Outermost_points=Convexhull_outermost_points on [XY, XZ, YZ]
Find number_outermost_points on each plane
Sort number_outermost_points in descending order
Find plane with max number_outermost_points % starting plane

% defining cut lines
 Project on starting plane
 Do TSP-GA to define cut line on first plane
 Project remaining points on second plane
 Do TSP-GA to define cut line on second plane
 Project remaining points (if any) on third plane
 Do TSP-GA to define cut line on second plane
```

Fig. 5 Pseudo code for Convex hull cut method



ANA Results	V	R	A	SC	#S	#P
Original	0.81	0.85	0.73	0.06	11	1
Convex Cut	0.83	0.93	0.78	0.73	4	3

Fig.6 Dissecting part using Convex hull method; (a) undercuts locations, (b) Outermost points for convex hull on xy-plane (c) Cut line (d) Cut plane (e) Remaining undercuts midpoints projected to second plane (f) Cut line (g) Cut plane (i) Dissected pieces. *V: Visibility, R: Reachability, A: Accessibility, SC: Setup complexity, #S: # of setups, #P: # of pieces

The algorithm consists of two main phases, finding the starting plane and then defining cut lines. The starting plane is defined by firstly projecting the mid points of undercuts to the three principal planes, XY, XZ and YZ planes. Next, the convex hull on each plane is calculated. The plane with the maximum number of outermost points will be the starting plane to define cut lines (Figure 6a, b). The remaining points inside the convex hull are projected on the next plane with maximum number of outer most points (Figure 6e) and then a third plane (if any points remain).

The cut lines are then determined by solving the TSP-GA for the outermost points projected on the starting plane first, where the minimum cost path that will visit all points will be obtained (Figure 6c). The process of defining cut lines is then repeated on the second plane (Figure 6f) and then the third plane if any points remain. Three cut lines at most can be obtained using this method. As in the previous method, the cut plane is defined by extruding the cut line along one line that is perpendicular to the cut line through the entire part depth (Figure 6d, g). Although this solution method will result in simpler cut lines and more machinable pieces compared to the first approach, the cut lines can be still complex (Figure 6c) leading to the same problems during joining processes as in the first approach. Therefore, the following third approach is proposed.

Third Approach: K-cluster- cuts

The k-cluster cut method utilizes the k-mean clustering and convexity test to define cut lines. This approach can result in more than one cut line, and consequently more than two subcomponents. The maximum number of cut lines that can be obtained will be one third of the number of available undercuts rounded up to the nearest integer.

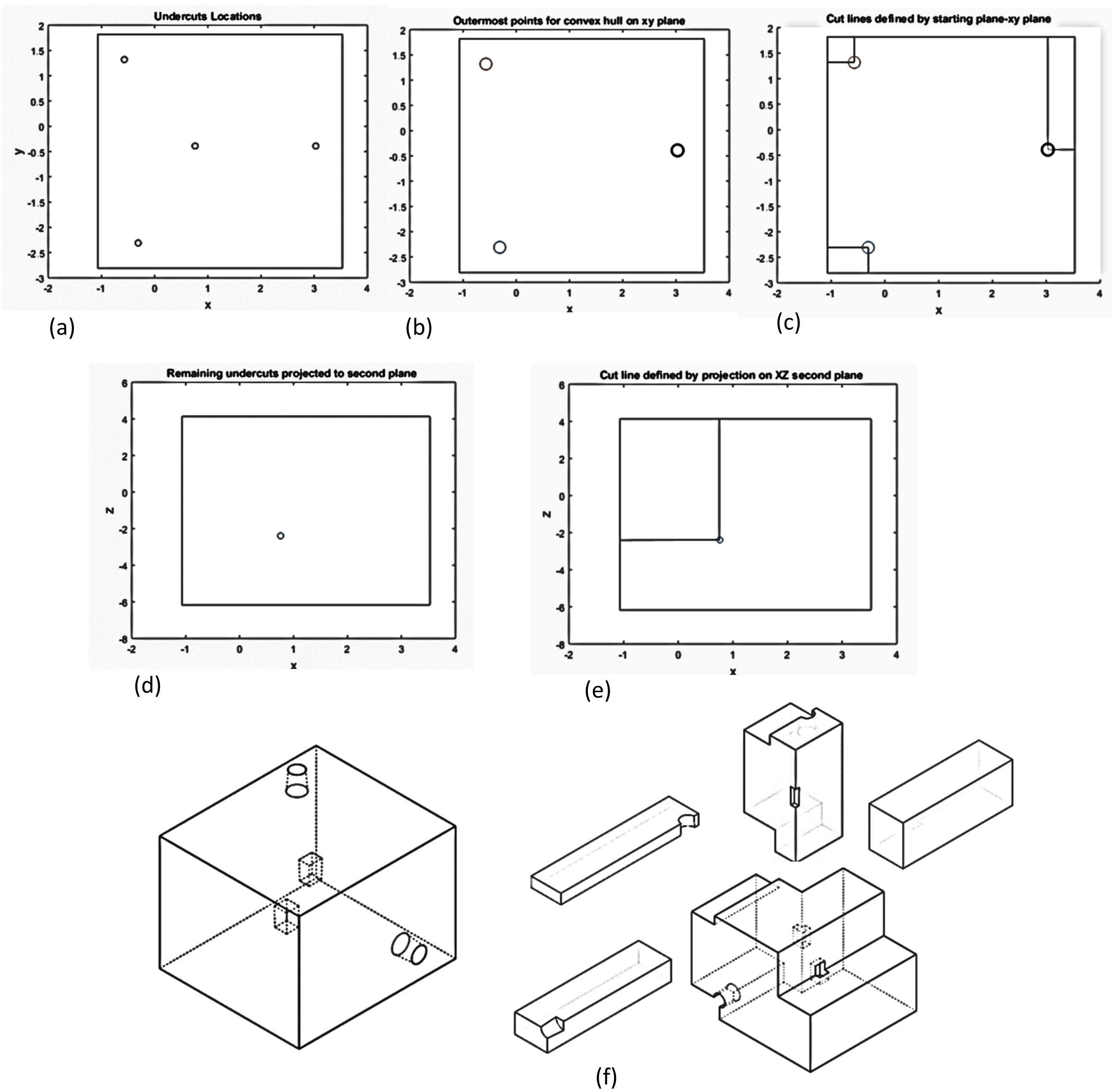
```
Get XYZ_vertices
Project vertices on XY, XZ, YZ
% starting plane
Find Convexhull [XYvertices, XZvertices, YZvertices]
Outermost_points=Convexhull_outermost_points on [XY, XZ,YZ]
Find number_outermost_points on each plane
Sort number_outermost_points in descending order
Find plane with max number_outermost_points
% cluster points on starting plane
Set k= clusters_number=number_outermost_points/3
Generate random k_clusters_centrodis =c
Do k-mean clustering
%defining cut lines
For i=1 to k
  Get vertices in each k
  n(i)=number of vertices in k
  For j=1 to n(i), step n(i)-1
   Get vertex (j,k)
   Find shortest path between vertex(j,k) and principle axes
   Return shortest path(j,k)
  End
Cut_ line (k) =shortest path(k)
Plot cut_ line(k)
End
```

Fig.7 Pseudo code for K- Cluster cut method

Figure 7 shows the pseudo code for the algorithm used to define cut lines using this approach. The algorithm starts by projecting the mid points on each of the three principal planes; XY, XZ, and YZ (Figure 8a). Next, the convex hull on each plane is calculated. The plane with max number of outermost points on the convex hull is then chosen to be the starting plane for defining cut lines (Figure 8b). The remaining points inside convex hull are projected on the next plane with maximum number of outer most points (Figure 8d) and then a third plane (if any points remain).

After determining a starting plane, the cut lines definition begins with clustering points into k clusters using k-mean clustering method. The k-mean clustering will partition points on each plane into k clusters where points will be grouped to the cluster with the nearest mean (Hartigan & Wong, 1979). This will help to have shorter cut lines which have the advantage of reducing weld line length later when joining the pieces. The number of clusters was chosen to be one third of the number of outer most points on that plane. The points in each cluster are then used to define cut lines.

The definition of a cut line in each cluster is completed by finding the shortest distance from the first point and the last point in each cluster to the boundary of the part. Examples of cut lines defined using this approach is shown in Figure 8c. The process of defining cut lines is repeated for the remaining points on the second plane (Figure 8e) and then a third plane. As in previous approaches, the cut plane is defined by extruding the cut line along one line that is perpendicular to the cut line through the entire part depth.



ANA Results	V	R	A	SC	#S	#P
Original	0.81	0.85	0.73	0.06	11	1
Cluster Cut	0.89	0.99	0.96	0.84	3.5	5

Fig.8 Dissecting part using K-cluster cut method; (a) undercuts locations, (b) Outermost points for convex hull on xy-plane (c) Cut line (d) Remaining undercuts midpoints projected to second plane (e) Cut line (f) Dissected pieces. *V: Visibility, R: Reachability, A: Accessibility, SC: Setup complexity, #S: # of setups, #P: # of pieces

This approach will result in simpler cut lines (Figure 8c) and more machinable pieces (Figure8f) than the previous approaches. However, a unique solution will still be obtained using this method where the part will be dissected into unique pieces that each has a unique position to occupy. More importantly, the pieces will have more flat contact surfaces near edges of the part. The existence of flat contact surfaces near part edges will help to alleviate weld joint inaccessibility problems, facilitate the addition of energy director features in case of welding pieces, and allow assembly of the pieces in more open (less constrained) space compared to previous approaches.

Solution evaluation

The quality of the solutions is evaluated using a design for manufacturability-based software called ANA. ANA consists of four modules for manufacturability analysis; machining, sand casting, die casting and welding. In this study, machining-ANA was used for evaluating the quality of solutions through assessing the dissected part's machinability. The machinability in ANA is defined by four metrics, the visibility (V), accessibility (A), reachability (R) and setup complexity (SC). The overall machinability score in ANA is calculated through weighted averaging the normalized scores for the four metrics. The

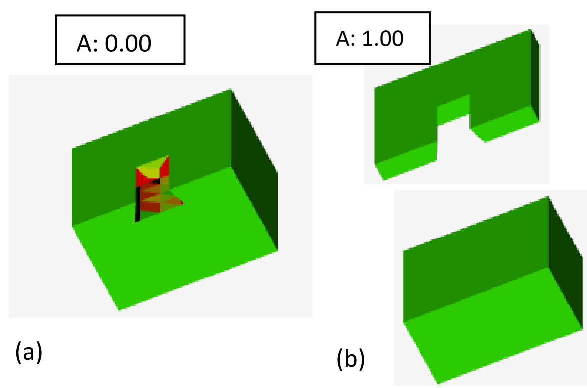


Fig.9 ANA output for Accessibility metric for a model (a) before dissecting, (b) After Dissecting

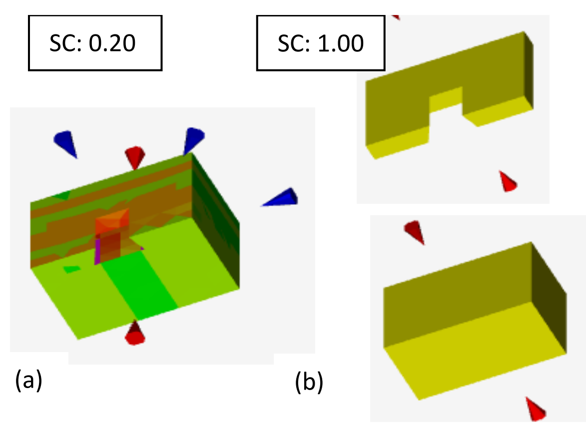


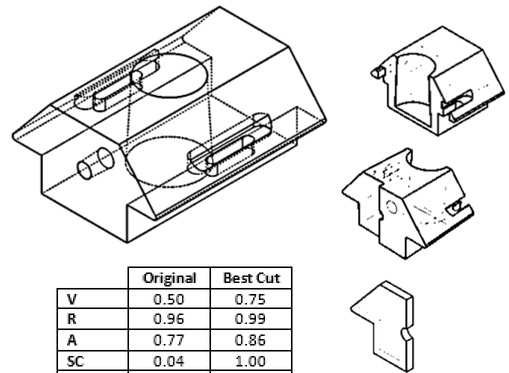
Fig.10 ANA output for Setup Complexity metric for a model (a) before dissecting, (b) After Dissecting

ANA output consists of both graphical and numerical results. The graphical results present design features in different colors representing their ease of manufacturing (from red to green). The numerical results include the individual numeric and normalized scores of each metric and aggregated score across the four metrics for a given process (Hoefer, Chen & Frank., 2017). In this paper, each piece was analyzed in ANA and then the score before and after dissection were compared. Example of ANA output for Accessibility and Setup Complexity metrics are shown in Figure.9 and Figure.10, respectively.

Implementation

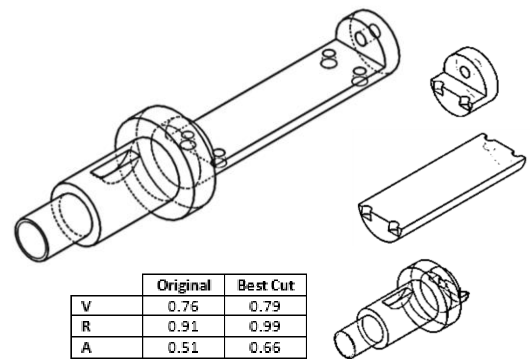
The three solution methods were built and implemented in MATLAB. Then, three different models with multiple undercuts were used to test the proposed methods and results of solution are presented. The original part models (before dissecting), the best dissected model and associated machinability parameters; V, R, A, SC, (number of setups) #S and (number of pieces) #P are shown in Figure11. Generally, the proposed k-cluster-cut method provided the best solution to dissect parts into pieces that have better visibility, reachability, accessibility, simpler and less setups compared to their single piece models. For example, Figure11a shows that the average visibility of dissected pieces improved by 50% compared to original part. Also, part dissecting simplified and reduced setups (from 15 to 2) needed to machine the dissected pieces compared to the original. As discussed before, the main advantage of the k-cluster-cut method is that the dissected parts will always have flat surface which will facilitate their fixturing for the purpose of machining and joining. Although, the k-cluster-cut method helped to make the test models more machinable through dissecting, more pieces of course result. Moreover, it should be noted that this method cannot guarantee the complete visibility of undercut surfaces in the dissected pieces (Figure 11).

This is due to the level of problem abstraction used to build the algorithm. In other words, the algorithm relied on the midpoints of the undercuts to define cut lines, ignoring other factors such as the size, the principle axes, and the orientation of undercuts which can explain incomplete visibility, reachability, and/or accessibility of the dissected pieces. Therefore, future research should focus on defining the appropriate level of problem abstraction that can provide a more complete and optimal solution. It is worth mentioning that although a low level of abstraction is more representative, it is always better to start with the highest level of abstraction as it was done in this study. That is, many factors may worsen solution since a more complex or even 3D cut line can be obtained, more piece can result, and less possibility of having flat surfaces compared to the currently proposed algorithm. To summarize, although too much abstraction is not good, a more comprehensive problem



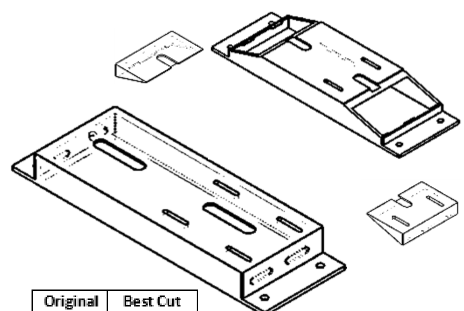
	Original	Best Cut
V	0.50	0.75
R	0.96	0.99
A	0.77	0.86
SC	0.04	1.00
# S	15	2.00
# P	1.00	3.00

(a)



	Original	Best Cut
V	0.76	0.79
R	0.91	0.99
A	0.51	0.66
SC	0.50	0.89
# S	4.00	2.3
# P	1.00	3.00

(b)



	Original	Best Cut
V	0.61	0.77
R	0.88	0.95
A	0.71	0.71
SC	0.17	1.00
# S	6.00	2.00
# P	1.00	3.00

(c)

Fig.11 Test Models dissected using proposed method. Best cut was chosen based on overall machinability.

definition could even harm more, therefore, it will be a good direction of future research to study which factors should be considered that can guarantee optimal solution.

Further, the cut planes in this study were defined by extruding cut lines along one line that is perpendicular to the cut line through the entire part depth. Therefore, future studies should focus on defining the depth of cut to reduce weld line length.

Conclusion

A new method to migrate designs from additive manufacturing to conventional machining is presented. This migration method focuses mainly on moving undercuts within a design from AM to machining through dissecting a part. Three different approaches were implemented to find the best sectioning/cut lines. The third approach (k-cluster cut) was the most favorable, especially with increasing number of undercuts. The cut lines defined using k-cluster cut were the simplest compared to the other approaches and resulted in better machinability parameters of pieces. Findings of this study should be of interest to design and manufacturing engineers since it can save time and effort while modifying designs, however, it has some limitations. First, the undercuts' midpoints were the only factor considered to define cut lines, hence the effect of other factors such as size, and orientation of undercuts on solution quality must be investigated in future. Secondly, the cut planes in this paper was defined by extruding cut lines through the entire depth of the part, thus future work should focus on defining depth of cut planes to have more unique solutions. Third, the ANA software was only used to evaluate quality of solutions, therefore, other metrics such as weld line length should be considered as evaluation metrics in future work. Lastly, this paper only dealt with migrating undercuts from AM to machining, so other features and processes should be considered in the future.

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GENERAL CONCLUSION AND FUTURE WORK

General Conclusion

This dissertation focused on three areas; design fixation related to additive manufacturing, treatment methods for design fixation, and a method to facilitate migration of a design from AM to conventional processes. Design fixation related to additive manufacturing was investigated through designing and conducting a user study with two groups (DFAM group and DFCM group). A fixation on non-producible features as well as harder-to-manufacture designs were noticed among the DFAM group. This shows that AM knowledge can have a negative effect on designer skills and requires some consideration and treatment. Design fixation on non-producible features will be problematic if the final manufacturing process for a current AM part will be a conventional manufacturing method. In order to treat design fixation caused by AM knowledge, 3D feedback from DFM-based software was evaluated in a user study. It was shown that the DFM-based software helped to reduce design fixation and improve machinability of modified designs. The feedback of the DFM software treated fixation through reducing mental effort of designers and helping them to capture areas in the design that need modifications by color coding, consequently facilitating the design migration. To further facilitate migration from AM to conventional processes, a new method was proposed to provide suggestions for design modifications. The proposed method focused on migrating undercut, non-producible features in a design by means of dissecting the design into pieces. The method was shown to be capable of dissecting designs into pieces that have a better overall machinability than the original single piece design. Some may argue that the problem associated with non-producible features can be solved if the design is modified in such a way that those features no longer exist, rather than increasing the number of components. This can be a solution if those features are non-critical for design functionality (less common). Instead, this work assumes that the current AM produced component was accepted and that required design features that must be preserved; we simply need to change manufacturing processes.

To summarize, considerable literature today discusses the advantages of additive manufacturing with respect to freedom in the design process. For the first time, this dissertation investigated the negative effects that AM can have and suggested a potential treatment method. This work highlighted that those negative effects of AM, called *design fixation* on non-producible features, can hinder an AM design from being converted to conventional methods, causing considerable financial or time to market losses. A treatment method was suggested based on DFM-based software feedback to mitigate the negative effects of AM knowledge and ease conversion. Also, a first of its kind migration method was proposed in this work to assist in migrating non-producible features of a design from AM to a conventional process through dissecting the design into manufacturable pieces.

Future Work

The work presented in this dissertation is some of the first of its kind in the literature. Although initial work is promising, there are numerous opportunities for improvements and future work; a few are suggested:

1) Both user studies in this work relied on recruiting and training engineering students to perform a simple design task, therefore, future research may focus on replicating the studies with professional designers using more complex design tasks.

2) This DFM-based feedback study focused on non-producible features and the manufacturability of designs in a machining process only. Other manufacturing processes such as casting should be studied in the future, so results can be generalized to other conventional processes.

3) The proposed dissection method utilized the undercuts' midpoints to define cut lines, thus the effect of other factors such as size, and orientation of undercuts on solution quality must be investigated. Also, the cut planes were defined by extruding cut lines through the entire depth of the part, hence future work should focus on defining depth of cut planes to have more unique solutions. Additionally, the ANA software (machinability) was only used to evaluate quality of solutions, therefore, other metrics such as weld line length should be considered as evaluation metrics.