DESIGN INSPIRED BY DIGITAL FABRICATION

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1. INTRODUCTION

In the world of art and design, the generation of ideas and fabrication of those ideas into objects for reflection and evaluation conceptualize creativity. Painters generate sketches as products of their creative process, exploring the possibilities of composition in the form of pencil drawings prior to a finalized painting. Architects explore many design possibilities through design sketching, hard-line drawings, physical models, and manufacturing artifacts for the exploration of diverse ideas. Today, many architects use digital design to manufacture shape and space including advanced technologies such as generative modeling methods with parametric modeling and CAD scripting (Sass & Oxman, 2006). Industrial designers, traditionally generate variety of ideas in the form of sketches to be able to better narrow down possible solutions of a problem statement.

Throughout the design history, many efforts have been implemented to facilitate the idea generation process. Previous literatures feature the variety of endeavors implemented ranging from creative methodologies to the high-end technological innovations. “Inkling” or “Cintiq” are true examples of this evolution.

From a technology-methodology perspective, there are still innovative technological advances as well as challenges in the application of design methodology in certain circumstances, which could be bridged together. Digital Fabrication (DF) technologies and specifically Rapid Prototyping (RP) appear to have extensive potentials to be integrated into the creative design process as they can offer the possibility of making tangible artifacts to existence where mind is unable to imagine.

This study intends to answer the question of formulating specific key aspects of the product design methodology by integrating with RP’s capabilities in a fabricating process of tangible solutions as a part of the creative design process. It then attempts to find those attributes of a design topic that qualifies the “Digital Model Fabrication methodology” (DMF) to be incorporated into a design project.

Designers always attempt to rationalize what they design. Making study models, mock ups and test prototyps are among approaches implemented to validate the utility of a design in a research process (Sachse, 2004). These methods are considered post-design evaluation methods. By the time a prototype is brought to a focus group session, many decisions have already been made. In other words, in a typical design process, critical decisions are made on the paper. Integration of micro design decisions shapes a product. What makes this process possible is the skill and the level of experience of designers to compile the final components of a product. Variety of design topics, however, makes it less feasible for designers to be able to successfully compile the components of a product system when the complexity increases.

From the other hand, designers are sometimes limited by their skills or several other parameters (Sachse, 2004). This attitude results in over-simplification of the outcome which reduces the efficiency of the product. Combining limitation and complexity makes it more necessary to have higher level of flexibility in the creative process of product design.

The main emphesis of this study goes toward the innovative side of the range of design topics. This orientation is mainly due to the existance of uncertainity within the non-redesign projects. This study also intends to explore differing possibilities and propose theoretical solutions for projects with the high level of complexity and it is beyond the time limitation of this study to evaluate the theory in all possible circumstances. Thus, the case study that was presented in this paper attempts only to simulate the proposed theory, and it is not aimed to discuss a definitive proof for the theory as it requires further research within a larger time frame.

2. BACKGROUND

Physical modeling is a way that designers realize mental concepts (Cuff, 1992). As Sass & Oxman (2006) say, as a design representational medium, the model making process can lead to new forms beyond the original concept. Computer model making has been a good interface between design ideas and product manufacturers. It also gives the capability of making surfaces with any complexity. The process of computer model making has been time consuming and it is the complex part in the design process. Rapid prototyping (RP) today is absorbed into practice and is being recognized as a significant technology for design (Sass & Oxman 2006). From the time, design schools began to use RP technologies, the interface between design ideas and producers, centered on the nature of the design process. According to the Sass & Oxman (2006) beyond the design-related and material-representational benefits of RP within overall design and fabrication processes, there also appears to be significant pedagogical benefits to be derived from these technologies.

Creative fields are characterized by the generation and manufacture of objects for reflection and evaluation (Schon, 1983). As the product of painter's creativities are their pencil sketching or oil paintings, designers' tool for this purpose is their sketching, hard-line drawing, physical models and manufacturing artifacts for the exploration of diverse ideas (Sass, 2005). Today, many designers use digital design to demonstrate their ideas. Laury Sass (2006) attempts to formulate certain key aspects of the design methodological frameworks that are coalescing with RP's capability to build artifacts as part of the creative design process. She concentrates on the emphases of conceptual stage materialization through RP and construction information modeling. It demonstrates a process of design situated between conceptual design and real-world construction (Sass & Oxman, 2006). In addition, RP may be used for finalized design presentation or to study complex forms as physical artifacts. Also she noted, RP-based digital design and digital fabrication defines the characteristics of both fields and the advantages that come from the integration of the two areas. On the other hand, Simodetti (2002) offered small-scale to full-scale manufacturing via RP accompany CAD-CAM methods of production. He illustrated the influence and advantage of full-scale mock ups in functional revelations and visual aspects through the cognitive development of design.

2.1. ADVANTAGES OF DIGITAL FABRICATION

Digital fabrication provides realistic opportunities for representing, evolution, and redesigning complicated forms. It extends learning in a digital design environment since designers will be engaged with materials and machine processes similar to industrial production. According to the Sass & Oxman (2006), it may also be said that the use of these appliances and software extends creative design beyond the early stages of design and supports the continuity of design through its various stages. Design materialization also has advantage in design that supports the inception of knowledge and the learning of design procedural structures (Evans 2005). Another advantage is the development of knowledge of shape and future possibilities for real scale 1:1 fabrication (Khoshnevis, 2004).

He emphasized on defining methods of working with RP in design process, which includes conceptualization, materialization, and fabrication design. Rapid Prototyping is now the most important tool for product designers that helps then demonstrate a product's functional and ergonomic considerations. These studies noted that the next revolution for RP would tie the two ends of the spectrum with generative technologies in both software and machinery. With "Digital Fabrication Methodology", modeling and RP will simplify methods to achieve high quality representations.

3. THE THEORY

The difference between the notion of 'complex' and 'complicated' is considered a complicated issue per se (Rodriguez-Toro et al, 2003). Our mind, naturally, tends to analyze problems by reductionism. In other words, we think about large notions by decomposing them into more simple components (Haghnevis, 2012). In the world of design, these simple components are to recompose to shape an integrated product through design process. Through the application of the theory of complexity in this research, it is intended to propose a comprehensive typology for possible modes of product design. With a close correspondence with engineering systems, product design could be broken down into four categories. These categories are conceptualized in the left diagram (figure 1).

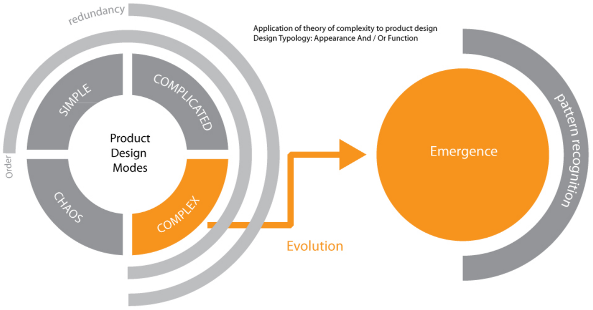

Figure 2- Theoretical framework

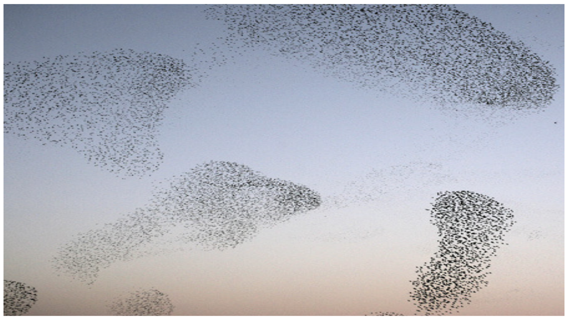

Figure 1 - Emerge of Pattern in a Flock of birds

These modes then will be used to form a theory trough, which the hypothetical digital fabrication oriented design process could be implemented. The categories illustrated above are considered for both product aesthetic and the function of a product system. However, cross combination of aesthetics and function is beyond the defined scopes of this research. Based on the complexity theory in a complex system, cause and effect are only coherent in retrospect, and do not repeat (Kurtz and Snowden, 2003). Complexity in design is generally considered in relation to component geometry where it has been studied for its influence in many areas (Rodriguez-Toro et al, 2003). Therefore, application of identical findings or phenomena in a creative design process can lead to radically different interpretations and commensurately different products. In contrast with other modes discussed above, complex cannot be applied to an existing product; rather, it is a mode in which a complicated product could be designed. On the other hand, the theory of complexity studies how patterns emerge through the interaction of many agents. Emergent patterns can be perceived, but not predicted. This phenomenon is called retrospective coherence (Kurtz and Snowden, 2003). This ultimately ends up emerging a pattern, which is recognizable but not predictable. Based on the theory of complexity, in the same system, patterns are not necessarily identical over time.

The picture (Figure 2) shows flock of birds, which are a well-known example for the emergence of visual patterns in a complex phenomenon. Although this is very abstract, it could be incorporated in design theory to describe many unexplained circumstances of the design process. From the design perspective, the pattern finding could be interpreted as ideation, creativity and solving problems.

3.1. COMPONENT COMPLEXITY

Complexity, basically, becomes important when the possibility for emergence increases. Component complexity includes those aspects of the design that relates directly to each component, but not directly affected by the entire system of product (Rodriguez-Toro et al, 2003). In this study, component complexity is categorized as either “macro components’ complexity” or “micro components’ complexity”.

Macro components are basically elements of a design project, while micro components are mostly tangible elements of a product per se. Instances of macro components are namely: manufacturing complexity, process complexity, human factors complexity, scale complexity, and assembly complexity (Sass & Oxman, 2006). Micro component complexity is beyond scope of this study as it does not necessarily result in a complex product system rather it makes a complicated one.

3.2. APPLICATION OF THE THEORY IN DESIGN METHODOLOGY

Final presentation and prototyping were the preliminary use of digital fabrication methods in design process. However, recent advancements in this area have made it an affordable desktop element of every design office. Since a tangible artifact enables designer to be exposed to unlimited perspectives and combinations, it becomes a high priority candidate to substitute traditional ideation tools. Because, based on the complexity theory discussed earlier in this chapter, the only provision required for a complex system to be moved toward emergence of a recognizable pattern, is to be exposed to unlimited configurations. An RP sketch would definitely offer this new and valuable capability to the design process. From the other hand, affordance of the technology makes it more feasible for the suggested use. In addition to the ideation use, the new tool helps designer learn more details and obtain more reliable evaluation data during the research phase due to providing tangible media as a research tool.

The main question still remained to be answered is: what design topics are qualified to be pursued through Digital Model Fabrication (DMF). By the use of an inductive ratiocination, two factors seem to be characterizing this argument. Based on the implications of complexity discussed earlier, component complexity and redundancy are needed to be present for an ordered pattern to emerge. Since a complex system cannot have a single component, the presumed provision for a topic to be qualified for DMF would be: “having more than two macro component with redundancy”.

4. CASE STUDY

The initial phase of this study focuses on developing a digital fabrication oriented methodology through applying current theory in the domain of product design methodology, and utilizing digital fabrication techniques. This methodology emphasizes on the precedence of digital fabricated 3-D sketches in the design process (see figure 4 & 5). Incorporating the mentioned design process, a hypothesis is developed and discussed.

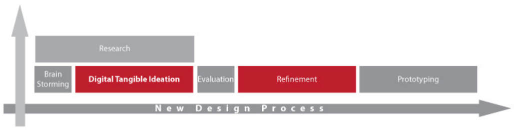

Figure 3 - Digital fabrication oriented design methodology

Figure 4 – Traditional Design Methodology

The next phase is to evaluate the effectiveness of the process through conducting two case studies. Each case study investigates different opportunities and challenges.

This case study was based on the results of projects implemented by two junior industrial design students at Arizona State University. Both projects address identical problems while each incorporates different design methodology.

The diagram (Figure 5) illustrates the traditional approach. This approach is used by the student implemented the "Case B". The other designer who implemented the "Case A" employed "DMF" process instead. They shares many steps with the except ideation and design development steps.

The product was a metal shear that cuts through different gauges and alloys of sheet metal with efficiency. It is used to cut straight or irregular lines/holes on various materials in sheet form. The most typical applied material would be sheet metal. The blades oscillate and mirror the mechanics of a pair of scissors.

4.1. CASE "A"

This project benefits from the new methodology, which allows the designer to use digital modeling and rapid prototyping as a substitute of the traditional ideation tools. The student was to explore potential improvements based on the initial research phase, and develop two primary ideas through digital fabrication techniques. A 3D surface modeling program called Rhinoceros was used for the student to conceptualize the product shape in a short period of time, but shelling the parts was a challenge with that program to create a solid model for 3D printing.

Figure 6 – Improvement opportunities

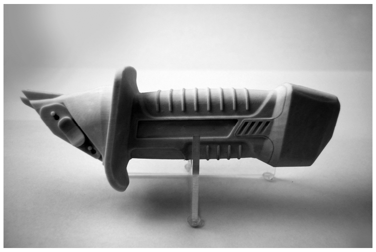

Figure 6 - 3D sketching

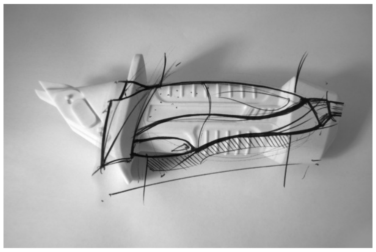

Figure 5 - 2D development

Figure 6 shows how primary research reflects the initial objectives of the project. The primary 3-D sketches then converted to a white physical rapid prototyped model. In this case a 3D printer (Z-Printer) was used to fabricate concepts, as the machine is known to be fast and cost efficient. These physical models then were used to conduct an interview with users. It enabled the users to touch the primary version of the product, and shared their experiences with the designer.

Inputs gained through the interview were applied to the primary concepts in the next step these manipulations took place in various aspects namely; human factors, aesthetics, function, usability, safety, performance and sustainability. The experience of design development in the DMF method appeared to be exciting. It was similar to a redesign process as designer manipulated the existing objects. Figure 7 illustrates the process of implementing the new aesthetics based on the 3-D sketch.

As illustrated in the above picture, the rapid prototype helped maintain the proportion of the original concept using the image of the prototype in a digital sketching process. In this case, the final appearance was adjusted based on the users' inputs in the way that a more fluid design language replaced a muscle care inspired ridged style. Based on the results of the study, a smoother design increased the sense of precision, which was desired by the potential users.

Human factors were among the highest priorities of this case. The actual model of the primary concept dramatically helped understand the ergonomic issues of the innovative concept. This was what mostly happens during the redesign projects. Figure 9 shows the angle issue of the first concept that needed to be improved.

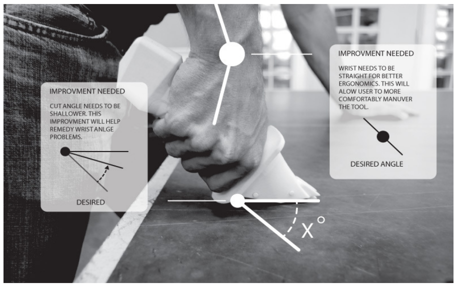

Figure 8 - Lessons learned from 3-D sketching (Angle Correction)

Figure 9 - Lessons learned from 3D sketching (Product Configuration)

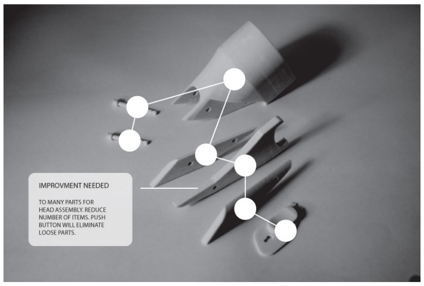

Figure 7 - Lessons learned from 3-D sketching (Mechanical Simplification)

Playing with 3D printed functional parts also brought up the opportunity to discover alternative ways of functionality. Finding a way to reduce the number of moving parts of the shear was among the achievements of this procedure, as moving and testing the real scale parts showed that two sets of parts were doing one job.

Figure 12 illustrates the final product designed through DMF. Overall, the characteristics of this design include: dynamic aesthetics elements, redundancy in functional parts and appearance, good product-user interaction, high priority ergonomics and many more.

4.2. CASE “B”

“Case B” follows the traditional design process. The process is formed upon the application of inspirational metaphors. More than 100 sketches before conducting the initial research shaped the creativity foundations. They have been followed by a primary evaluation.

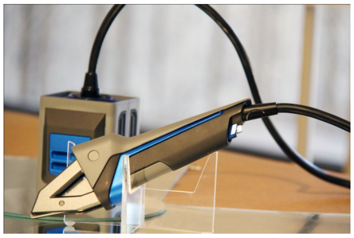

Figure 11 - Final product (Case A)

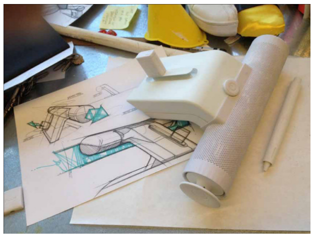

Figure 10 - 2-D Sketch & 3-D mock up (Case B)

A handmade model of the selected concept was then created out of blue foam using known subtractive techniques. This is what used for a secondary evaluation, nevertheless; the concept was rejected based on the users’ inputs.

Apparently, it is very hard to communicate 2-D sketches driven from one or more metaphors with users. Their reaction to concept changed when they experienced the study model. This led to unreliability of research data in this case. As a result, the designer ended up with developing the third concept, which employs a totally different technique for cutting sheet metal (figure 16). The final concept functioned similar to a plasma cutter. It consumed water as the main fuel, breaks it up into hydrogen and oxygen, which was ignited. Aesthetically, it was elegant and minimal but very conservative. Overall, it shows series of human factors, safety, performance and functional problems. The process took longer time. Compared to the “Case A”, it had more but shorter steps. The final concept did not go through any secondary evaluation or development process.

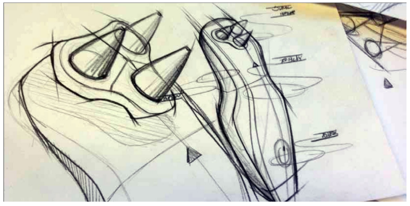

Figure 13 - 2-D Ideation (phase two) (Case B)

Figure 12 - Study model – (phase two) (Case B)

Figure 14 - Final product (Case B)

Despite all these shortcomings, it offers a better quality of product-user interaction through a simple user interface. In other words, the idea enables the user experience series of simple and familiar activities to perform a technical task. Figure 16 illustrates the final product design through the traditional methodology. Overall characteristics of this design include: conservative aesthetic elements, minimal and simplified design, average product-user interaction, and low priority ergonomics.

5. ANALYSIS

The case study and data analyzed in this study is to answer the following question: if the digital tangible modeling can reduce the component complexity phenomenon in the product design process and how. It is, however, out of the scope of this study to validate all parameters of the theory. Human factors complexity appears to be an instance for the component complexity, which was addressed in the case study and analysis.

5.1. RESEARCH AND EVALUATION

Decision-making and evaluation are critical points in a user-centered design process. In a successful project, designer evaluates achievements and innovation according to the parameters learned in the research to ensure a reliable outcome. Thus, an evaluation effectiveness analysis could be a beneficial. Both cases were compared based on two parameters: accuracy and reliability of evaluation. To better analyze the effectiveness of the evaluations and to have a comprehensive comparison, a biaxial qualitative diagram was used to map the outcomes of the evaluation carefully based on the both parameters shown above. As featured in figure 17 (left), case "A" appears to be more successful in evaluation phase and case "B" demonstrates unreliable results, but at the same time stands in a neutral position from accuracy stand point.

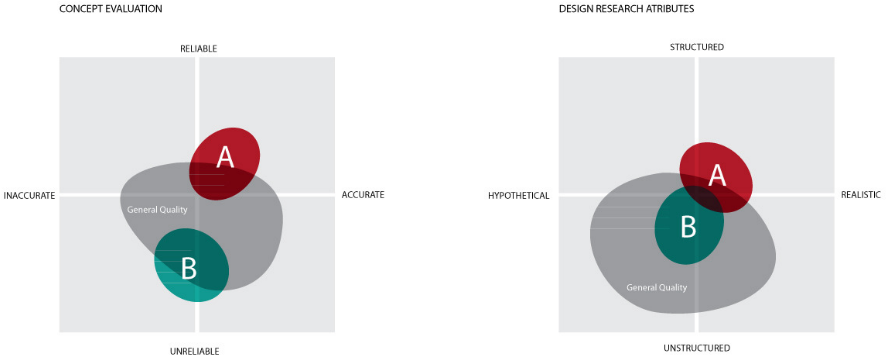

Figure 15 - Qualitative comparison of evaluation and research

This interpretation is mainly based on three levels of failure occurred in case "B" (Primary ideation, Study model and Final product). Limited time allotted to each activity compared to what's needed, could be assumed as one possible cause for this extreme difference. Higher precision of digitally fabricated sketches, from the other hand, seems to have a significant impact on reliability and accuracy of decision-making.

Various research methods were employed within both cases to obtain the user's feedback to validate preliminary and processed solutions over the design process. To characterize the contribution and effectiveness of design research in this case study, a biaxial map with four zones was developed (figure 17- right). These zones include: structured, unstructured, hypothetical and realistic which address two differing aspects of the research; the research design and the research outcome. Once again, case "A" appears to be more successful in this area. The research is more structured which generally results in shorter research timeframe. Simultaneously, results are more realistic. Increased level of tangible features has definitely had a positive influence on obtaining more realistic outcome with minimum effort. This could be considered a positive contribution of DMF methodology, which has been beyond the theoretical expectations of this study. In both diagrams, the gray areas represent an average assumed for ID projects.

5.2. TIMING

Although both cases look at the same design problem, the different design methodologies used in these two cases have made a significant difference in the actual timing of them. Based on the actual recordings, "Case A" shows fewer time consumed for all phases which were different from project B. Common activities, however, have taken nearly identical time for both designers, even though some tasks have been implemented individually.

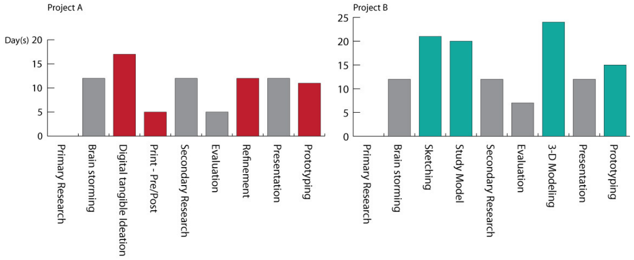

Figure 17 - Timing comparison

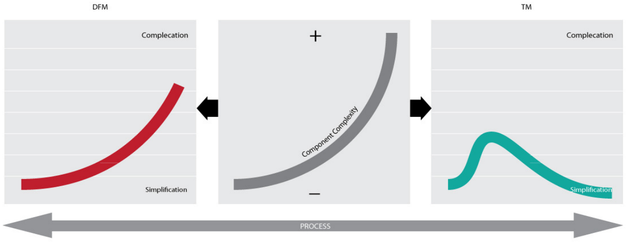

Figure 16 - Redundancy to complication ratio

Despite the qualitative effect of the new design methodology, the case study features a considerably shorter overall timeframe for the project “A”, compared to project “B”. Based on figure 18, the effective overall time spent on project “A” was 86 days while this time for project “B” was 119 days. In order to better generalize this result, looking in depth at single tasks is required in both projects to develop a qualitative interpretation.

5.3. COMPLEXITY ANALYSIS AND REVERSE IMPACT

Complexity analysis in this case study can be implemented using several parameters and compared against the level of component complexity. These parameters must be extracted from each case and may not be valid in a similar case study. The most significant result of the component complexity in this case study appears to be an overall tendency of simplification in TM as redundancy increases. A close comparison of the final products features dramatically different results. The reaction of the designer in case "B" is to simplify the component to overcome the redundancy while in case "A", there is a gradual increase in the overall complication as redundancy increases over the design process. Use of primary geometric shapes in case "B" in contrast to complicated functioning shapes in case "A" is a consequence of this undesired simplification approach in case "B". Rapid prototyped sketches appear to have significant role in helping the designer in case “A” to have a better understanding of the components which consequently prevents the designer from deleting the problem rather than solving it (See figure 19).

6. CONCLUSION

Considering the concept of learning through doing, this study proposed a new product design methodology entitled “Digital Model Fabrication” (DMF). This methodology ensures an extensive use of rapid prototyping as a tool to generate breakthrough ideas in a timely manner. In analyzing the data obtained from the case study and applying the principals of the complexity theory simultaneously, it becomes apparent that the new methodology could be more advantageous when the project is faced with a complexity in one or more components. As an instance for the concept of complexity of components, the case study featured that in application the DMF methodology to a project with human factors priorities, more reliable outcomes and more effective solutions are accessible. Moreover, it could increase the time efficiency in such topics as well. The below diagram (figure 20) is created to visually conceptualize the relationship between the increase of redundancy to complexity and overall efficiency of each methodology based on the results of the case study analysis.
It is important to have a deep understanding of the actual dimensions of a project before deciding to use DMF.
What learned through this study is important because the current research has not fully addressed the effects of DMF process on the efficiency of a design project. While Sass & Oxman (2006) bring up a concept similar to DMF, they have not evaluated the impacts of the theory on design methodology.

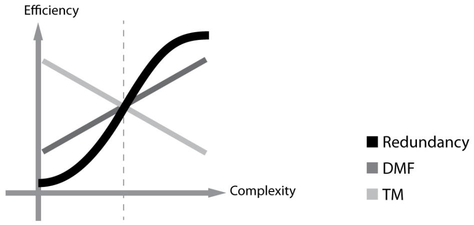

Figure 18 – Redundancy to efficiency ratio for DMF and TM (Traditional Methodology)

Based on the current findings and those reviewed, DMF could serve as a powerful methodology when a reliable creative design solution is desired for a design complex. It also featured that DMF cannot be considered as an effective methodology for circumstances with simplicity. Furthermore, this study proposed parameters in form of a theoretical framework to better understand the appropriate circumstances in which DMF acts as an effective methodology.

The results of this study support Sass & Oxman (2006) which stated, digital fabrication oriented design improves the current status of design, which is situated between conceptual design and real world manufacturing. Not only does DMF facilitate design activities, but also validates the creative process of designing products, as it bridges the creative design activities with engineering. Thus, DMF can serve as one of the future tools in both research and design practice. While this study should not be considered an ends-all for design methodology in industrial design, it can be an important step as every advancement in this area brings us closer to a design methodology that meets the expectation of the 21st century.

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