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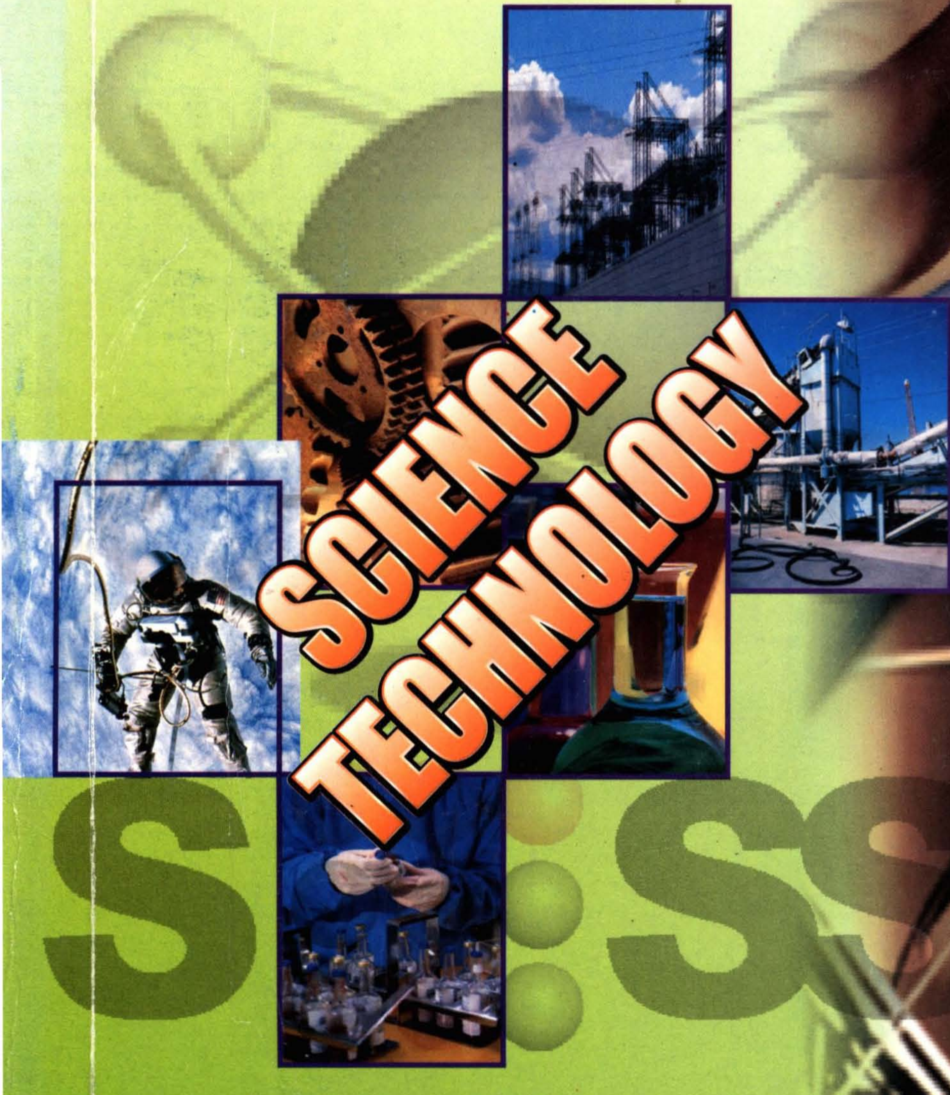

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A Study of the Effectiveness of Adapting Fused Deposition Modelling (FDM) in Industrial Design Process

Firdaus Zawawi
Marzuki Hj. Ibrahim

ABSTRACT

The principal objective of this study is to assist Industrial Designers to improve the quality of prototype and design process through the recommendation of guidelines from an industrial design perspective. The approach adopted in this research was a study of the process of producing prototypes using different FDM machines by three selected organisations. Two phases of data collection were employed in this study: literature search and review (Phase One) and case study (Phase Two). Case studies included semi-structured interviews with senior staff directly involved in industrial design process. With this, a set of detailed descriptions of effectiveness of adapting FDM in industrial design process were obtained. FDM machines were chosen for comparison because at present it is one of the successful technologies to produce a prototype, representing with non-toxic materials, easy to process, simple, accurate and fast. The case studies focus on six important factors derived from Peschges (1999) research: 1) Preciseness, 2) Surface Quality, 3) Cost Corridor, 4) Time, 5) Suitability for Geometry and 6) Practical Features. The findings showed that they produced durable prototype, which are smooth surfaced and complete layer, thin layer, with cost savings and reduce build time, as well as wide suitability for geometry, practical features achieved by improving surface quality through sanding, polishing and painting the prototype. This research concludes that FDM machine model Quantum is the best machine to fulfil the requirements of quality prototype produced. Finally, it is hoped that this research will benefit any individuals or organizations involved in industrial design process.

Keywords: *Industrial design process, prototyping, Fused Deposition Modelling*

Introduction

A widely accepted definition of industrial design that has emerged is the ICSID's definition formulated by Dr. Thomas Maldanado in 1964 (in Bainton 1986):

> *Industrial Design is a creative activity which is aimed at determining the formal qualities of objects produced by industry. These formal qualities include the external features but are principally those structural and functional relationships which convert a system to a coherent unity both from the point of view of the producer and user. Industrial Design extends to embrace all aspects of the human environment which are conditioned by industrial production.*

British Standards 7000 (BS 7000 1989) states that the practise of industrial design involves the integration of engineering elements of new product development through verbal descriptions, sketches and *prototypes* which is concerned with the visual appearance on how the product will look like and the way it interfaces with the customer like how it looks, feels, smells or sounds.

Prototype is a functional three-dimensional object representation the visual appearance of products produced in the embodiment design phase of design process (BS 7000; 1989). Designers often produce the prototypes at embodiment stage of the design process to resolve overall geometrical, dynamic and safety issues, and to develop more complete layouts of the concept by taking into consideration each assembly, subassembly and component in turn.This is critical to the success of the design, which takes a lot of time and be adequately addressed before initiating the expensive business of detailing every component for the manufacturing of the product.

Prototypes fulfil can act as communication media for discussions with clients, potential customers or other company staff. They can help the designer develop new product ideas, especially when the new product is complex and highly three-dimensional and therefore difficult to visualise on paper. They also can be used to test products in order to verify designs (Wohler 2000).

Rapid Prototyping

Rapid Prototyping (RP) is a relatively new class of technology used for rapidly producing prototype from three dimensional CAD data. It is possible to fabricate almost any geometry of any complexity, because of the way RP systems build prototypes, which is layer by layer, using material such as plastic, paper, wax, etc. This is in contrast to conventional technologies which cut a block of material e.g. foam, wood, metal, etc. RP processes can also be used for the direct fabrication of production prototypes that go into end-use products. Object sizes currently addressed by this technology range from microscopic to entire buildings (Wohler 1999, and Kidd 1997). This technology is also known as Freeform Fabrication, Solid Freeform Fabrication, Layered Manufacturing, Desktop Manufacturing and so forth (Lamancusa 2001, Wohler 2000, Kidd 1997 and Kai & Fai 1997).

The Importance of Rapid Prototyping

Nowadays the need to speed up the prototyping process has become an important task for designers in order to reduce the time in industrial design process. According to Wohler (1999) with RP machines, prototyping can be produced in days instead of weeks or months when using conventional process. This finding was further supported by Selk (2001) who stated that RP techniques are methods that allow the designer to quickly produce physical prototypes with the important benefit to reduce the time to market. By using these techniques, prototypes can be built by just using the skill of individual craftsmen for no more than just the finishing part. Furthermore, the resulting design cost will be decreased considerably.

The approach adopted in this study was to study the effectiveness of adapting FDM in the design process. FDM was chosen for comparison because at present it is one of the successful technologies to build the prototype. According to Stratasys Annual Report (2001), FDM machine are easy to use. This was supported by Kai & Fai (1997). FDM technology is not involved with cleaning and post curing. Furthermore, it is dealing with non-toxic materials and the processes are fairly simple in which supports that are created can be easily broken away when the model is completed, for examples, in the Automatic support generation and Break-Away Support System. FDM can also be installed in an office environment where its operation does not require any special facility. Thus, FDM modelling process is simple, accurate and fast.

There are six suggested factors to be used in evaluating a good prototype as derived from the concept of Pechges' research in 1999. The factors are preciseness, surface quality, cost corridor, time, suitability for geometry and practical features. In this respect, the guidelines recommended for evaluating a good prototype would be beneficial to industrial designers, higher institutions of learning and organisations. These guidelines when applied to industrial design process will improve the overall design process.

Research Methodology

Two phases were involved in this study: literature search and review and case study. The main purpose of the literature review was to form a firm base on which to develop an understanding of the research area and establish the originality and viability of effectiveness of adapting FDM in industrial design process. A literature search of previous work was carried out in areas related to: 'FDM' and 'industrial design processes'. This helped to widen the understanding of the current situation of FDM and industrial design process globally. At the same time, as much information as possible was collected regarding effectiveness of adapting FDM in industrial design process including current practice abroad. Other than that literature search and review in Phase one are used to give the researcher initial ideas to formulate questions for case study interview.

The initial selection of companies to be contacted for the case studies was based on a directory found from the FDM machine supplier. Nine organisations were selected and contacted for case studies. Based on the initial visits and the reactions of key personals in each organisation, five organisations were short listed and contacted for further discussions. Eventually three organisations were selected for the full case studies analysis. The number of participating establishments was limited to these three organisations due to their positive responses. The three organisations which were finally selected were:

1) TNB Research Sdn. Bhd. (TNBR);
2) Technology Park Malaysia (TPM); and
3) Universiti Islam Antarabangsa Malaysia (UIAM).

Criteria for Selection of Organisations

The process of selecting and identifying suitable organisations for the case studies was based on the following criterias: (1) Establishment of the Technology Usage. All of the three selected organisations are using FDM technology. FDM Quantum machine is used in TNBR while UIAM chose to use FDM 2000 and TPM had chosen FDM Prodigy to build the prototype. (2) Systematic Approach to Design Process. Three case studies selected were based on following a chronological systematic approach to design processes as suggested by British Standard Institution (1989) for effective new product development. (3) Permission and Willingness. Case studies were selected based on the ability in gaining access into the organisations and where respondents were willing to co-operate with the researcher. In this way, the researcher is likely to be able to build trusting relationships with the participants in the study and data quality and credibility of the study are reasonably assured.

Source of Information

The method known as *'triangulation'* was used to collect data for the case studies. By using this method any dispute to the validity of the data would be counteracted as stated by Atkinson (1983). The data for the cases were, thus, collected through three inter-related stages: (1) Interviews. The case studies began with interviewing the key respondents who were product designers, engineers and modeller operators and were directly involved with the industrial design process. In this case study, semi-structured interviews were adopted. A set of standardised focused questions were adopted in the interviews during the case study. This was to ensure that each respondent's replies could be analysed systematically. This approach also makes data analysis simpler as it is possible to organise questions and answers that are similar (Patton 1987); (2) Direct observations. This is the second stage of data collection. This provided additional and relevant complementary information about the topic under study. In the present study, the formal data such as observations during the visits to the case study 'sites' and during the interviews with the respondents were collected. (3) Examination of physical artefacts carried out at the study sites. Physical artefacts were the third source of evidence central to this study, and have been used extensively here. In this study, the prototypes were evaluated at certain phases of the production process. Although evaluation can be made to the prototype that undergoes the complete production process, a step-by-step evaluation guarantees more accurate results. By examining the completed prototypes, the researcher was able to develop a broader perspective concerning all of the machine applications, beyond that which could be directly observed in a short period of time. The following section discusses and explains the process of data collection of the case studies.

Discussion of Case Study Interview

Majority of the interviews were conducted during the period of August through October 2003. A total of three semi-structured interviews were conducted with respondents who are familiar with the industrial design process at the three organisations. The primary aim of these interviews was to provide a set of detailed descriptions on effectiveness of adapting FDM in industrial design process. Prior to each interview, respondents were sent information about the project and its aims. In this way, views expressed in the interviews will reflect a prior knowledge of the purpose of the project.

The Role of the Three Case Studies

The case study field work which involved three successful organisations focused on six important issues: (1) Preciseness, (2) Surface Quality, (3) Cost Corridor, (4) Time, (5) Suitability for Geometry, and (6) Practical Features. These were derived from the Pechges (1999) research. Based on these issues, six aims of case study research were considered. The first aim was to investigate the preciseness of the prototype through the prototype building style and layer smoothness The second aim was to analyse the surface quality in relation to layer thickness. The third aim was from the aspect of consideration on the cost corridor which is how the organisation selects the RP machine and reducing the cost of producing quality prototype. The fourth aim was the factor of time which is the consideration on producing the most complex and non-complex prototype. The fifth aim was on the suitability for geometry which is the classification of the complex and non-complex prototype. The final aim was to study the practical features which are the finishing processes in terms of sanding and painting.

Case Studies Results

From the analysis of case studies interviews, direct observations and physical artefacts at the three organisations, the researcher found that there was sufficient evidence to suggest that similarities and differences did exist. The key similarities of the selected three organisations with regard to the effectiveness of adapting FDM in industrial design process were evidence when they arranged the prototype in vertical positions in the build envelope to reduce the support structure and to produce the prototype which are more durable. Moreover, this can produce prototype with a good shape. The thickness of layer was all set to 0.17 mm in the FDM machine and a complete layer of prototype was produced by them. They also used the prototype produced for direct testing and tooling.

By using FDM machine, they unanimously agreed that the production cost can be reduced by half. According to them, the most complicated prototype to be built was the hollow type (Class 2) where as the simplest was the cover type (Class 7). During the post-processing process they finished the prototype by sanding the surface of the prototype using sandpaper. Then sprayed the prototype with primer colour then paint it with the selected colour.

In contrast, the key differences between three organisations with regard to the effectiveness of adapting FDM in industrial design process could be depicted when TNBR took only about 12 hours in the building process of complicated prototype (Class 2) whereas both UIAM and TPM took about 17 hours. In building simple prototype process (Class 7), TNBR took only 2 hours compared to 2 hours 50 minutes taken by both UIAM and TPM.

The similarities and differences between the three organisations (in qualitative terms) were found to corroborate with direct observation and physical artefacts. Six important observations were noted from the analysis of case studies interviews.

1. It was evident that all the organisations arranged their prototype in a condition with less support structure.
2. Customers' requirement or final application of the prototype played a major role in determining the durability of the product produced.
3. The prototype was also produced in complete layer in which set at 0.17 mm measurement was set for each layer.
4. Mostly the prototype produced by FDM machine was used for testing.
5. Sandpaper was used to sand the surface and primer colour was sprayed onto the prototype followed by the painting of selected colour.
6. Differences of building process for both simple and complicated prototype occurred as a result of using different types of FDM machines in the three organisations studied.

Synthesis of Findings from Case Studies Results

As stated earlier, six important issues were taken into consideration namely Preciseness, Surface Quality, Cost Corridor, Time, Suitability for Geometry and Practical Features were taken into consideration in the case study field work. The syntheses of the findings are as followed.

Preciseness

Preciseness can be divided into two categories, building style and layer smoothness. Building style can further be divided into two, durable prototype and thickness of layer. Building style influences the preciseness of the prototype. All three organisations oriented the prototype in the same manner. It was oriented vertically in the build chamber to reduce support structure and to get a more durable prototype. The three organisations had set their machines with 0.17mm layer thickness so that a precise prototype could be produced. As of layer smoothness, all the organisations had produced smooth surfaces and a complete layer prototype by using the FDM machine.

Surface Quality

Surface Quality is important for better functionality and visualization, and is becoming increasingly crucial with more prototypes being used for end purposes (Vasudevarao et al 2000; Kai & Fai 1997). Every organisation set 0.17 mm as the layer thickness of the prototype which the surface produced is middle stage and the finishing process to produce smooth surface is easier.

Cost Corridor

Cost Corridor is divided into two, cost and production. All organisations in this study rely on FDM machine because it can produce the prototype which can use directly for testing and tooling. Time reductions by half of the production cost were gained by using FDM machines. Time and cost savings ranged from 50 to 90 percent depending on the size of production.

Time

The time frame concerns the completion time of the prototype depending on the machine system used. In this research study, TNBR took only 12 hours to produce a complicated prototype that took UIAM and TPM 17 hours, meanwhile two hours were taken to produce a simple prototype by TNBR but both UIAM and TPM took 2 hours 50 minutes.

Suitability for Geometry

The classification of prototype structure is important to determine its Suitability for Geometry. All three organisations classified the complicated prototype as class 2 (hollow type) which uses support structure to produce the complete prototype. In contrast, they classified the non-complex prototype as Class 7 (cover type). Observations showed that this is due to the use of minimal support structure.

Practical Features

Practical Features can be divided into two, post processing and painting. Post processing concerns the process of sanding and polishing with sandpaper (Shellabear 1998, Kai & Fai 1997). It is essential to avoid the prototype from being distorted. From observation, before these processes could be carried out, the three organisations used plier and cutting knife to take out the support structure from the completed prototype. Then they used sand paper to smooth its surfaces. Painting is applied fairly easily on prototypes made of plastics. This process is done mainly to improve appearances or for presentation purposes. The three organisations sprayed primer colour onto the prototype followed by the chosen colour.

Recommendations

Formulated via qualitative research findings, the following recommendations of effectiveness which focused on factors identified by Pechges' research in 1999 can be implemented in improving design process and the quality of prototype.

Prototyping Process

The prototype must be arranged in the vertical order in the build envelope to reduce the support structure and to make the prototype more durable thus producing a prototype in a good shape. The layer thickness must be set at 0.017mm in the FDM machine to get the preciseness of the prototype. For further analyses of the preciseness of the prototype, the finished prototype must be in complete layer. To ensure that the prototype have a good appearance, it is vital to sand it using sand paper during the post processing, then sprayed in primer colour before the selected colour is applied. These four processes must be strictly followed to improve the design process and the quality of the prototype.

Factors for Evaluating Good Prototype

There are six suggested factors to be used in evaluating a good prototype as derived from the concept of Pechges' research in 1999. The factors are preciseness, surface quality, cost corridor, time, suitability for geometry and practical features. In this respect, the guidelines recommended for evaluating a good prototype would be beneficial to industrial designers, higher institutions of learning and organisations. These guidelines when applied to industrial design process will improve the overall design process.

Improving Conventional Design Process

In conventional design process, the processes are not integrated into one another because the processes are done manually. Nowadays, there is a better choice by using CAD which can generate a prototype directly from the machine through a transfer of computer data. Therefore, with the application of the new design process, it is recommended that organisations can produce and market their products faster and will be able to compete in the international market.

Design Education

Until recently, design education follows the conventional design process. It is recommended that educators use a new direction in design process as it can accelerate the overall process and produce good prototype through the application of FDM machines.

With that, it is hoped to produce students with experience and knowledge of the latest design process and technology. Other suggestions are by having joint-venture projects between organisations and design departments in university/college as an ad-hoc member. Students will be exposed to the actual working environment and are, thus, able to adapt themselves to the real world of industrial design practice.

Industry

In the area of research and development (R&D), for organisations which are involved in industrial design process, FDM can be effectively adapted to produce good prototypes and also to improve the design process. It is recommended that FDM Quantum is used in producing good prototype. This is because it is found that FDM Quantum meets all the six factors of effectiveness that had been identified in this study.

In view of the high cost involved in purchasing the machines, organisations can opt for alternatives such as acquiring services from selected service bureau. Organisations do not necessarily have to bear the cost of purchasing the FDM machines. Instead, by commissioning design jobs to selected service bureau will speed up the design process. It will also modernize the conventional process of producing prototypes. This will contribute to the production of prototype using FDM machine widely.

It is also suggested that the Council which promote industrial design process to the industrial sector used prototypes produced by FDM machines during their promotion.

Conclusion

The researcher believes that most of the recommendations are suitable to be adapted in organisations involved in industrial design process. However, the adaptation and implementation of these recommendations depends entirely on the organisations themselves. It is hoped that they can consider and possibly implement the recommendations made in the light of improving their prototype and industrial design process which will then not only profit their organisations but the nation as well.

It is hoped that this research is beneficial to organisations which follow the industrial design process and that this has made some positive contributions towards the strategy for improvement of the industrial design process for industrial designers. It is also hoped that this enables the industrial designers and organisations who follow the industrial design process adopt new strategies and working practices in order to achieve improvements in contemporary measures of preciseness, surface quality, cost corridor, time, suitability for geometry and practical features. It is also hoped that this study helps to create long-term competitive advantages in terms of effectiveness of adapting FDM in industrial design process.

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FIRDAUS ZAWAWI, TNB Research Sdn. Bhd., Research Institution Area, Bangi, Selangor. firdaus@tnb.com.my

MARZUKI HJ. IBRAHIM, Faculty of Art & Design, Universiti Teknologi MARA Kelantan.