Tool for Teaching Physical Model Making in Product Design

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Abstract. As physical prototypes and models can solve many design issues during the New Product Development (NPD) process, it has been introduced as an essential course in many design schools. With the advancement of 3D CAD technologies students find it easier to make digital models, but they find the physical prototyping and model making difficult. This difficulty arises due to lack of understanding of materials, processes and product form correlation required for physical prototyping. In order to address this issue, a tool has been developed and introduced to design students. The tool would guide them to select materials and processes, based on the product form. The tool is a matrix of variables viz. product form, processes and materials. To formulate this matrix, altogether three hundred fifty numbers of products were considered, and clustered them according to their form and processes. On this basis, possible materials have been identified for fitment and suitability of the processes. The tool has been tested with two groups of design students in the course of ‘modelling and simulation’. The effectiveness of the tool has been analysed by conducting an independent t-test and also the Felder-Silverman Index of learning. It has been observed that the tool is highly effective. This paper discusses this effort in details.

1. Introduction
Physical model making is used for different purposes in different disciplines. With the technological advancement, the model making process has changed over time, but physical model making is the process, which is still used by designers in professional work and continues to be embraced [1]. Physical model making is extensively and continuously used by product designers because models are not merely a representation method, but it also makes complex realities comprehensible, operational and workable. Models can also act as exploratory devices by working as self-communication tools and allowing new questions to be raised, alternative solutions to be explored, hypotheses to be formulated [2]. The construction of 3D physical models has some advantages for the product design engineer, such as: visualizing design concepts, communicating ideas, stimulating creativity, aiding understanding, identifying real fabrication difficulties, allowing form modifications and form generation. In product design students learn through ‘learning by doing’, and model making helps them to take the idea “out of the paper” for visualizing it better and especially for making it tangible [3]. Despite that, novice product designers are not using models or prototypes always in all design phases [4]. Novice product designers are considering prototypes to be made towards the end of the design process to test and evaluate only, rather exploiting the advantages of prototypes in the whole design process [5]. This is true also for the Department of Design, IIT Guwahati. This paper illustrates the research work to overcome issues regarding physical model making for students in design.
2. Problem in physical model making
Prior research explicates that novice student has a narrow perception of a prototype [6], but it is also important to check the understanding of prototype making among novice designers. To identify the problems faced by design students for physical model making a study was conducted with students of the second year second semester Bachelor of Design students of the Department of Design, IIT Guwahati. For the rest of the paper, these students will be considered as Batch1. There were a total of 36 students in the Batch1. These students were admitted through the Joint Entrance Examination of India. They all had taken the same basic courses offered by the institute in the first year. In the second year odd semester also they all had taken the same core courses offered by the Department of Design. It is important to mention that they all had a compulsory course Material and Processing. The study was conducted in four steps. These are:

- Step 1. Students of B.Des II year were asked to select iconic furniture design to make a model of it.
- Step 2. Students were allowed to use workshop facility (machine tools, hand tools, equipment and instruments required) to prototype, but to take suggestions or help from workshop instructors.
- Step 3. Qualitative data of the output of the individual students were recorded.
- Step 4. Students were asked to write about their experiences (good/bad) of model making.

After the study, all the students’ voices were converted into technical voices. These are represented in Table 1:

| Problems                                           | Frequencies |
|----------------------------------------------------|-------------|
| 1. Problem in the selection of material             | 10          |
| 2. Problem in the selection of processes            | 8           |
| 3. Problem in the selection of both material and processes | 9           |
| 4. Problem in the selection of hand tools           | 2           |
| 5. Problem in the selection of finishing material   | 2           |
| 6. Problem in the selection of finishing techniques | 1           |
| 7. Others                                           | 4           |

To overcome come such issues and facilitate students in physical model making, a structured tool is required. Aiming to make a structured tool to help beginning design students, a systematic literature review was carried out.

3. Background study
Systematic background study had been done as defined by Okoli and Schabram [7].

3.1 Purpose of the Background Study
The intended objective of conducting the systematic literature review was to identify the drivers, principles or guidelines and support tools for model making. For this, the following definitions were considered:

- Drivers in the model making are those dimensions, which are intrinsic or extrinsic to prototype and prototyping process [8].
- Design principles, guidelines or heuristics are criteria, method or decision factors, which give direction to a particular process [9].
- Tools [10] are an implement that you employ to increase efficiency in one or several phases of the process in the form of manual, framework, card or computer-based application. In this context, background study had been done for universal principles or guidelines for design tools also, which will help in making a structured tool for model making.
3.2 Practical Screen
Total one hundred and thirteen references were searched and sixty research publications were selected after filtering. The considered literature spans from 1983 to 2019, where 52% (31 items) of the considered publications are from journals, 25% are from books or book chapters, 20% are from Conference Proceedings and only 3% are from Gray literature.

3.3 Data Extraction
Data had been extracted from the considered literature based on three aspects: 1. Drivers, 2. Principles/ Guidelines, 3. Tools.

3.3.1 Drivers: To understand the drivers in model making, it is very important to understand the characteristics of the model/prototype of model making/prototyping process.

Houde and Hill [11] presented a model which represents what prototypes model/prototype. The model represents a three-dimensional space, which corresponds to important aspects of the design of an interactive artefact. He defined three dimensions of the artefacts as 1.role; 2.look and feel; and 3.implementation. “Role” refers to the function, with which it is useful to the user. “Look and feel” denotes the sensory experience of using an artefact. “Implementation” refers to the techniques and components through which an artefact performs its function. Moreover, Lim [8] describes the anatomy of model/prototype with two different dimensions such as filtering dimensions and manifestation dimensions. Filtering dimensions give an understanding of what to filter and consider while crafting a prototype. But it is also important to consider how to make a model/prototype. Material, resolution and scope determine the specifics of how to make a model/prototype.

3.3.2 Principles/ Guidelines/ Criteria in Model Making/ Prototyping Otto and Wood [12] suggested a list of criteria while selecting materials for prototyping. These are 1. Cost, 2. Availability, 3. Ability to accept changes, 4. Ease of use and forming capability, 5. Scalable geometry, Scalable properties.

3.3.3 Tools (Support) for Model Making/Prototyping. In the recent past, Jessica Menold proposed a framework for prototyping to support the product design process, but it does not have any support tool or method [13]. There are other frameworks available, but Posada [3] is the only design educator, who proposed a tool where material selection is based on the process of addition of material or subtraction of material. This tool does not allow students to select material and processes based on a wide variety of forms.

3.4 Synthesis of Extracted Data
The insight from the background study is illustrated in Figure 1. The figure shows the relationship between filtering dimension, Manifestation dimension, Principles, Processes and related tool.

![Figure 1. Relationship between filtering dimension, Manifestation dimension, Principles, Processes and related tool](image_url)

Background study reveals that the tool must explain the material and processes based on the appearance (form) and function, considering the prototyping principles.
4. Development of the tool

With the help of extracted data, a tool was developed to facilitate model making in furniture design (TfMM 0.1-Tool for Model Making 0.1), where material selection can be done based on dominating form and primary elements such as bar, body and surface. Followed by material selection, related process selection, hand tool and machine tool selection is also possible in the developed tool. The tool was developed systematically. Various steps for developing the tool were as under:

- Step 1. Total 350 number of iconic chairs were grouped based on forms (Figure 2). Chairs, which were not possible to group on the basis of forms, they were grouped on the basis of the processes or the common material used. A total of 40 number of groups were formed.

![Figure 2. Grouping of chairs based on forms, materials or processes](image)

- Step 2. The furniture of each group was further grouped based on the dominant element [14] between bar, body and surface [15] as shown in Figure 3.

![Figure 3. Furniture with (a) Surface dominant, (b) Bar dominant, (c) Body dominant](image)

- Step 3. Based on the groups, appropriate materials, processes and hand tools were assigned.

The entire process of coding was done by three coders, who are having more than eight years of experience in product design teaching. The inter-rater reliability was checked by Cohen’s Kappa (k=0.85).

The final card-based tool has three columns such as form, material & processes and hand tools. The column form further divided into three rows such as bar, body and surface. Based on the types of furniture, novice designer can select material & processes and related hand tools (Figure 4).
5. Teaching with the tool

Students were asked to make a prototype of any iconic chair as per their choice, with the help of the developed tool. The developed tool was introduced to the Batch 2 of 50 students of the second year, second semester and the qualitative outcome was recorded (Figure 5). It was observed that the developed tool facilitate students in prototyping.

6. Testing of the tool

An independent t-test was conducted to check the impact of the tool. Independent t-test was done between two groups Batch1 and Batch 2 [16]. There was a total of 36 students in the Batch1 and 50 students in Batch2. The tool was not introduced to Batch1, but the tool was introduced to Batch 2 students. The outcomes of both batches students were scored on a scale of 1 to 10 (Table 2). A panel of three external faculties did the scoring process. To test the assumption of normality, we did the Shapiro-Wilks test (Table 3).
Table 2. Scoring Scale

| Grade      | Exceptional | Excellent | Very good | Appropriate | Clear | Satisfactory | Marginal | Rudimentary | Insubstantial | Insufficient | Deficient |
|------------|-------------|-----------|-----------|-------------|-------|--------------|----------|-------------|----------------|--------------|-----------|
|            | 10          | 9         | 8         | 7           | 6     | 5            | 4        | 3           | 2              | 1            |           |

Table 3. Tests of normality

| Group     | Kolmogorov-Smirnov<sup>a</sup> Statistic | df | Sig. | Statistic | df | Sig. |
|-----------|------------------------------------------|----|------|-----------|----|------|
| Batch1    | .205                                    | 36 | .001 | .900      | 36 | .003 |
| Batch2    | .175                                    | 50 | .001 | .931      | 50 | .006 |

For the above case, where a = .001, given that p = .003 for the Batch1 and p = .006 for the Batch2 – we would conclude that each of the levels of the Independent Variable (Stress Condition) are normally distributed.

To check the homogeneity of variances a Levene’s F Test was conducted (Table 4). It was found that the F value for Levene’s test is 3.058 with a Sig. (p) value of .084. As the Sig. value is more than our alpha of .05 (p > .05), it was concluded that there is no significant difference between the two group’s variances.

Table 4. Independent Sample Test

| Levene's F Test for Equality of Variances | t-test for Equality of Means | 95% Confidence Interval of the Difference Lower |
|------------------------------------------|-------------------------------|-----------------------------------------------|
| F                                        | Sig.                          | Mean Difference | Std. Error Difference | Lower |
| Equal variances assumed                   | 3.058 | .084 | -4.096 | 84 | .000 | -1.27556 | .31138 | -1.89478 |
| Equal variances not assumed               | -4.299 | 83.922 | .000 | -1.27556 | .29671 | -1.86561 |

The results of the independent t-test indicated that there is a significant difference in performance score between the two groups, t(84)=-4.096, p =.000096. These results suggest that individuals in the Batch2 (M = 7.22; SD = 1.58166) scored better than individuals in the control group Batch1 (M = 5.9444; SD = 1.16972) after the introduction of the tool [17]. The size of this effect (d = -0.9170), as indexed by Cohen’s (1988) coefficient d, was found to exceed the convention for large effect size (d = .80).

7. Learning from the tool
The Tool for Model Making (TfMM) was designed to facilitate novice designers and it has some explicit and implicit learning component.
7.1 Explicit learning from the tool

- Learning about the physical prototyping
- Understanding of required material and processes according to the form

7.2 Implicit learning from the tool

- Types and constructs of furniture

To check the effectiveness of the tool in a course, students’ response to Felder-Silverman index of learning [18] was recorded based on the four domains such as processing information, perceiving information, receiving information and understanding information. The average score is illustrated in Figure 6, Figure 7, Figure 8 and Figure 9.

Figure 6. Felder-Silverman Index of learning for Processing Information in Active-Reflective Scale

Figure 7. Felder-Silverman Index of learning for Perceiving Information in Sensing-Intuitive Scale

Figure 8. Felder-Silverman Index of learning for Receiving Information in Visual-Verbal Scale
Figure 9. Felder-Silverman Index of learning for Understanding Information in Sequential-Global Scale

The tool was developed to learn prototyping techniques by active self-engagement and students’ response (Figure 6) shows that they processed information by making prototypes. The developed tool has structured information with examples and the majority of the students perceived information through that (Figure 7), however, a group of students (Total No: 10) found that the grouping of the furniture also triggers ideas to develop new furniture. Students also received information from the verbal information given in the tool, but few students received information from the visual information (Figure 8). The tool also helped them making prototype sequentially, by selecting material and process (Figure 9).

8. Future scope
It was observed that the tool may be used as furniture design heuristics and it will be tested for its effectiveness as design heuristics for new furniture development. Future work will identify the aspects of design heuristics and refine the tool for a new version as heuristics.

9. Discussion and conclusion
When we are discussing 4th industrial revolution and prototype driven innovation [19], it is very important to empower beginning designers with the knowledge of manufacturing and processing for prototyping. The TfMM is developed towards prototype driven innovation for the beginning designers to provide the manufacturing and process know-how. The tool TfMM was developed from an analysis of existing chair geometries and the tool is then used to prototype existing chair again because the derivation was done by product design expert and hence it is important to check whether students understood the tool or not.

The tool has three-segment ‘form’, ‘material and processes’ and ‘hand tool’, where form guides the material and process selection. The effectiveness of the tool was tested through a t-test and it was found that the developed tool is fulfilling its objective to guide students for prototyping.

In the first version of the tool, a set of 40 cards were developed (Figure 10) and these are mentioned in Table 5. This is a unique tool in the field of product design (specifically furniture design) and will be helpful for product designers.

As the tool was developed by grouping furniture based on the forms and geometries, it also triggers ideas for a new design, which indicates that the tool may be used as heuristics [20] for developing new forms of furniture. The effectiveness of the tool as design heuristics has to be tested scientifically and qualitatively in future.
Table 5. List of the cards

| Polyhedron             | Space Truss           | Wave Surface          |
|------------------------|-----------------------|-----------------------|
| Origami                | Shaft to Blade Loop   | Reinforcement         |
| Street Pattern Tower   | Cantilever            | Continuous Block      |
| Hollow                 | Transformed Uniform Grid | Transformed Non-Uniform Grid |
| 3D Print               | Tensile Surface Structure | Möbius Loop         |
| Stack Body             | Stack Bar             | Stack Surface         |
| Tensegrity             | Hand Fan              | Bulge/ Swelling       |
| Wiggle                 | Bent Surface          | Peeled Surface        |
| Stud Surface           | Locked String or Rope (Knot/ Knit/ Weave) | Brush Stroke |
| Nervous System         | Revolving Bundle      | Comet Structure       |
| Locked Cushion (Knot/ Knit/ Weave) | Swollen Street | Bulge Surface |
| Genealogical Tower     | Bars & Panels         | Collapsible           |
| Inflatable             | Flat-Pack             | Log-Joint             |
| Transformed Body       |                       |                       |

Figure 10. Tool for Model Making Cards

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