CLASSIFYING PHYSICAL MODELS AND PROTOTYPES IN THE DESIGN PROCESS :

A Study on the Economical and Usability Impact of Adopting Models and Prototypes in the Design Process

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ABSTRACT

This paper discusses model making approaches in the design process and also classifies broadly the different types of physical models and prototypes. It also describes the fundamental principles of different methods of model making and prototyping and questions how they can be used in the conceptual and detailing design stages of the design process. The first part of this paper explains how physical model and prototypes are classified and why it is so important for gaining a better understanding of the designed product in terms of usability and technical functionality. The second part of this paper focuses more specifically on how these tools are helpful or restrictive in facilitating the creation of ideas, concepts and detailed design solutions following the various stages of the design process. Finally a user-centered and cost-efficiency design perspective will be discussed with respect to what extent models and prototypes are able to facilitate design changes throughout the different stages of the design process.

KEYWORDS: models, model making, prototyping, prototypes, design process

1. INTRODUCTION

Since the emergence of formalised Industrial Design practice, modelmaking and prototyping has been considered to be an indispensable tool for professional designers. The comprehensive range of modelmaking and prototyping methods is being used to stimulate creativity and develop the functionality and appearance of a product before it goes into production (Hallgrimsson, 2012). It is a tool, which enables designers to reflect on their design activities and explore the design space, while taking into consideration aesthetic, ergonomic, market and production issues. In other words, modelmaking and prototyping is a way for designers to explore form, composition and functionality from idea to detail design. Physical model making and prototyping is one the most recognised and accepted approach that has always been used by the designers to visualise and communicate their design solutions. Vail (2001) mentioned in his article that the concept of prototyping as a field of study and practice was firstly introduced in 1947, when Chuck Yeager designed the Bell X-1 aircraft. He used prototypes to test a 50-caliber bullet flying at supersonic speed, which was meant to emulate the Bell X-1. This historical event was referred to as “a bullet with wings”. After this historical event designers and engineers have been creating models and prototypes to translate and improve their ideas into three dimensional realities for the past centuries. Although the emergence of CAD has gained a significantly strong foothold in industrial and engineering design in the past few decades, with respect to visualisation, evaluation and realisation of products (Hallgrimsson, 2012), physical models and prototypes are still indispensable, especially when the designer wants to assure him or herself through tactile experiences with the product (Earnshaw and Jones, 1995). In this context, Marks (2000) and Kelly (2001) supports the existence of physical models and rejects the notion of ultimate dependency on virtual models as tools for solving all design problems.

Hence in real life project models and prototypes are still leading and getting more acknowledgement than 3D computer rendered and animation models (Hallgrimsson, 2012), because models and prototypes will assist in face to face interactions among different stakeholders, such clients, designers and consumers. Through physical interaction, these models will also provide more intricate information about the design as to highlight unforeseen problems.

There are various definitions of model making and prototyping from literature. According to Hallgrimsson (2012) model making and prototyping are different activities, even though they are in principal associated. He defines prototyping as a design method that uses physical prototypes to study and test how a new product will be used, and how it will look in a "manufactured state". Alternatively, he defines model making, as a step by step method for producing the prototype (Hallgrimsson, 2012, p.7). According to Kelly (2001), prototyping is defined as problem solving. It is a kind of culture and language. One can prototype just about anything; a new product or service, or a special promotion. Therefore, he strongly recommends designers should frequently use physical models in design process. Other designers such as Hasdogan (1996), Terstiege (2009) and Kojima (1991) define model making as a logical next step in the thinking process for every design idea. This means that when someone starts using materials and fabrication techniques, they are able to refine their ideas better. This implies that each person is served by a modelmaking approach, when they need to translate an idea into a physical reality.

After reviewing how different designers and researchers have defined models and prototypes, one may say that models and prototypes are essential tools for testing a typical concept or design on its use and appearance. Besides that, they also have the complementary function to enrich respective design processes and activities, with or without the involvement of stakeholders, especially when it concerns designer – client relationships.

With respect to manufacturing, prototyping is important to anticipate how products can be produced and assembled as efficiently as possible. Within the materialisation and pre-production stages, prototypes will mostly be used to test and measure the final design proposal according to the design requirements and to make sure that it functions, technically as well as from a use perspective.

In this article the following research questions will be addressed:

RQ1: How do designers classify physical model and prototypes and how does it help them in the design process?

RQ2: To what extend do designers use model making and prototyping to communicate their design with different stakeholders throughout their design process?

RQ3: How instrumental are models and prototypes in facilitating design changes throughout the different stages of the design process from an economical perspective?

2. The importance of model making and prototyping

Models and prototypes can be described as a “designer’s multi-dimensional expression.” This means that designers can use models and prototypes to express their ideas in accurate and precise manners to others. (Kojima, 1991). Similarly as “a picture tells a thousand words”, “prototypes are worth a thousand pictures”. (Kelly, 2001). Kelly also mentions in his research that prototypes are wonderful tools for understanding tangibility.

Good prototypes not only communicate with people, but also possess the leverage to persuade people. According to Hallgrimsson (2012) prototypes are playing an important role for designers in order to allow them to physically see the idea in 3D form, and therefore an essential medium for problem solving in design. He added that it is important for the designers to prototype and built models, because it assists the designer to identify and solve potential problems. Furthermore, Kojima (1991) elaborated why physical models are important because it allows designers to experiment with form, material and context, before moving on to the next stage. Complementary, the insight gained on materials and construction methods will prospectively influence how the actual product should be manufactured in future, taking costs into consideration.

3. Classification of models in design

As mentioned earlier, various designers and design researchers have adopted different ways of classifying models. Kojima (1991) classified models according to the following categories: image models, rough mock-up models, presentation models and prototype models. However, Ullman (2003) introduced another way of classifying models based on their functionality, which is (1) proof of concept, (2) proof of product, (3) proof of process and (4) proof of production. Furthermore, Ulrich and Eppinger (2012) classified models according to four simplified versions: soft model, hard model, control model and prototype. Reference to Ulrich and Eppinger´s classification, Viswanathan and Linsey (2009) and Mascitelli (2000) also used similar ones. However, the latter reverted back to a 4 level classification, comprising of (1) initial rough models, (2) refined models, (3) formative prototypes and (4) refined prototypes.

After examining different classifications of models and prototypes, the following classification, as shown in table 1, has been proposed based on what designers are most familiar with in their design practice.

Table 1: Classifications of models based inputs from several sources.

Soft Model	Hard Model	Presentation Model	Prototype
● rough modelling ● use to assess the overall size, proportion, and shape of many proposed concept. ● constructed from dense sculpting foam. ● fast evaluation of basic sizes and proportions ● reshaped and refined by hand to explore and improve its tactile quality	● technically non-functional yet are close replicas of the final design ● very realistic look and feel ● made from wood, dense foam, plastic, or metal are painted and textured ● have some “working” features such as button that push or sliders that move	● model that constructed and matched from CAD data or control drawing ● complete model and fully detailed composition of the product ● Component of this model will be simplified or neglected due to cost or time shortages	● high-quality model or functioning product that is produce to realize a design solution. ● would be tested and evaluated before the product is considered for production.

3.1 Soft Model

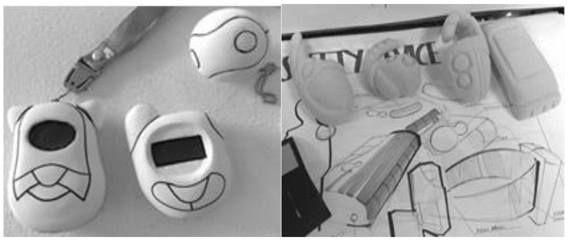


Figure 1: sample of soft model. (Source from Industrial Design class project UiTM, Malaysia year 1 students, 2009)

According to Ulrich and Eppinger (2012), a soft model is an initial and rough representation of the design intent where the aim of the designer is to show something rather quickly than accurately. Soft models are normally used to assess the overall size, proportion, and shape of several concept proposals. Soft models are usually constructed from dense sculpting foam, when it concerns representing monolytical objects in the beginning stages (Kojima, 1991). However, all kinds of easy to deform materials can be used for evaluating basic sizes and proportions in a quick manner. At this stage, the design is reshaped and refined by hand to explore and improve its tactile qualities through a more reflective way of making and analysing. Hereby, improvements are made on basic sizes, shapes and proportions for subsequent developments. This means that soft models are instrumental for designers to develop their first ideas and concepts as well as to determine clear directions for the next creative stages of the design process.

3.2 Hard Model

Similarly to soft-models, hard models are technically non-functional (Ulrich and Eppinger, 2012). However, they are more accurate replicas of the final design in terms of appearance. Materials used for hard model are normally wood, dense foam, plastic, or metal. To a certain extent limited functionality may be incorporated in the model to demonstrate important usability aspects of the design, for example, push-up button or moving sliders etc. Kojima (1991) also stated that hard models are used to visually compare and analyse more advanced design ideas and concepts. From a marketing and consumer research perspective, hard models complement advertising campaigns, and are therefore useful to gauge how potential user and customers respond to prospective products.

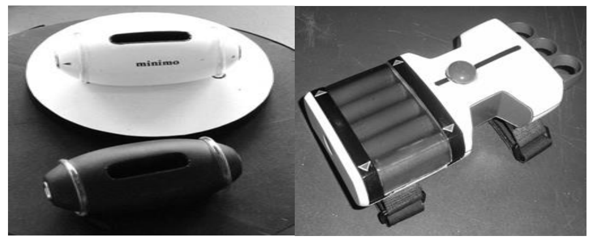


Figure 2: sample of hard model. (Source from Industrial Design class project UiTM, Malaysia year 2 students, 2008)

3.3 Presentation Model

Van Doren (1940) mentioned in his book that presentation models can be considered as the final embodiment tool for creative design and conceptualisation. In other words, it embodies all the designer´s decisions with respect to usability, aesthetic and marketing qualities of the designed product, which are relevant for communicating to the client. This statement is agreed upon by Kojima and Tano (1991) when they mentioned that presentation models should provide the exact image and detailing of the final product in order to facilitate an effective and responsible final decision making process. Kalweit et al. (2011) also added that in these final design stages, the model will be constructed and verified using CAD data or control drawing, presenting fully detailed composition of the final product. Where justified, elements of the model will be simplified or omitted to save prototyping time and cost. Although “Presentation Models” are explicitly discussed by Van Doren (1940) and adopted by Kojima and Tano (1991) in their book, many designers and researchers have difficulties to classify this category of models. Kalweit, et al.

(2011) referred to it as semi-prototype models whereas Ulrich and Eppinger (2012) renamed it control model. In other words presentation models can be interpreted as a “water downed” version of a full fledge prototype.

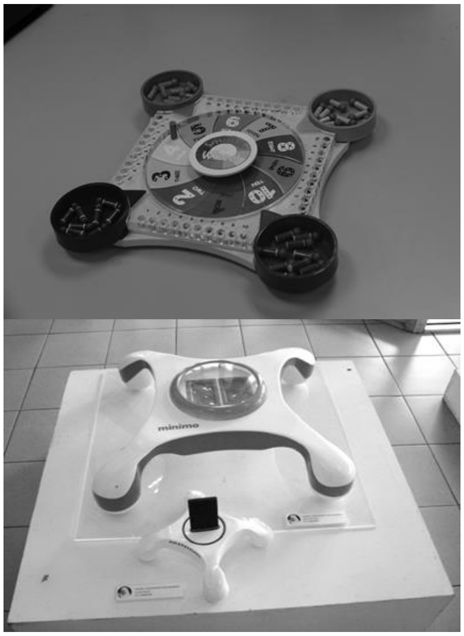


Figure 3 : sample of presentation model .(Source from Industrial Design class project UiTM, Malaysia year 3 students, 2008)

3.4 Prototype

Ulrich and Eppinger (2012) define prototype as “an approximation of the product along one or more dimensions of interest,” These dimensions are characterised as physical versus analytical and comprehensive versus focused. An analytical prototype is a non-tangible model, for example a mathematical model, whereas a physical prototype is an object, which looks similar to the final product. A focused prototype represents only parts of product, whereas a comprehensive prototype will provide a holistic representation of the final product before production. Evans and Pots (2004) further emphasized that Prototypes usually demonstrate a high-level of functionality, which is representable to the final design solution. This automatically implies that a Prototype, given today’s technology and production challenges, needs to be constructed from CAD data. Hereby, it is expected that prototypes are an exact or even better representation of the final product in terms of materials, construction, functionality appearance, etc.

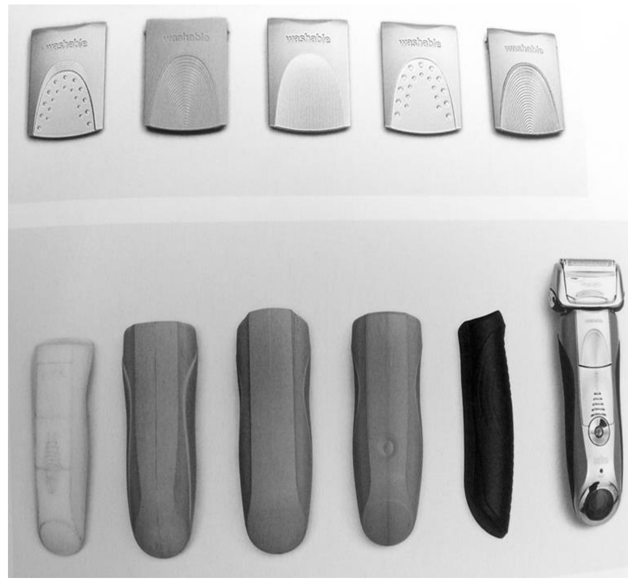
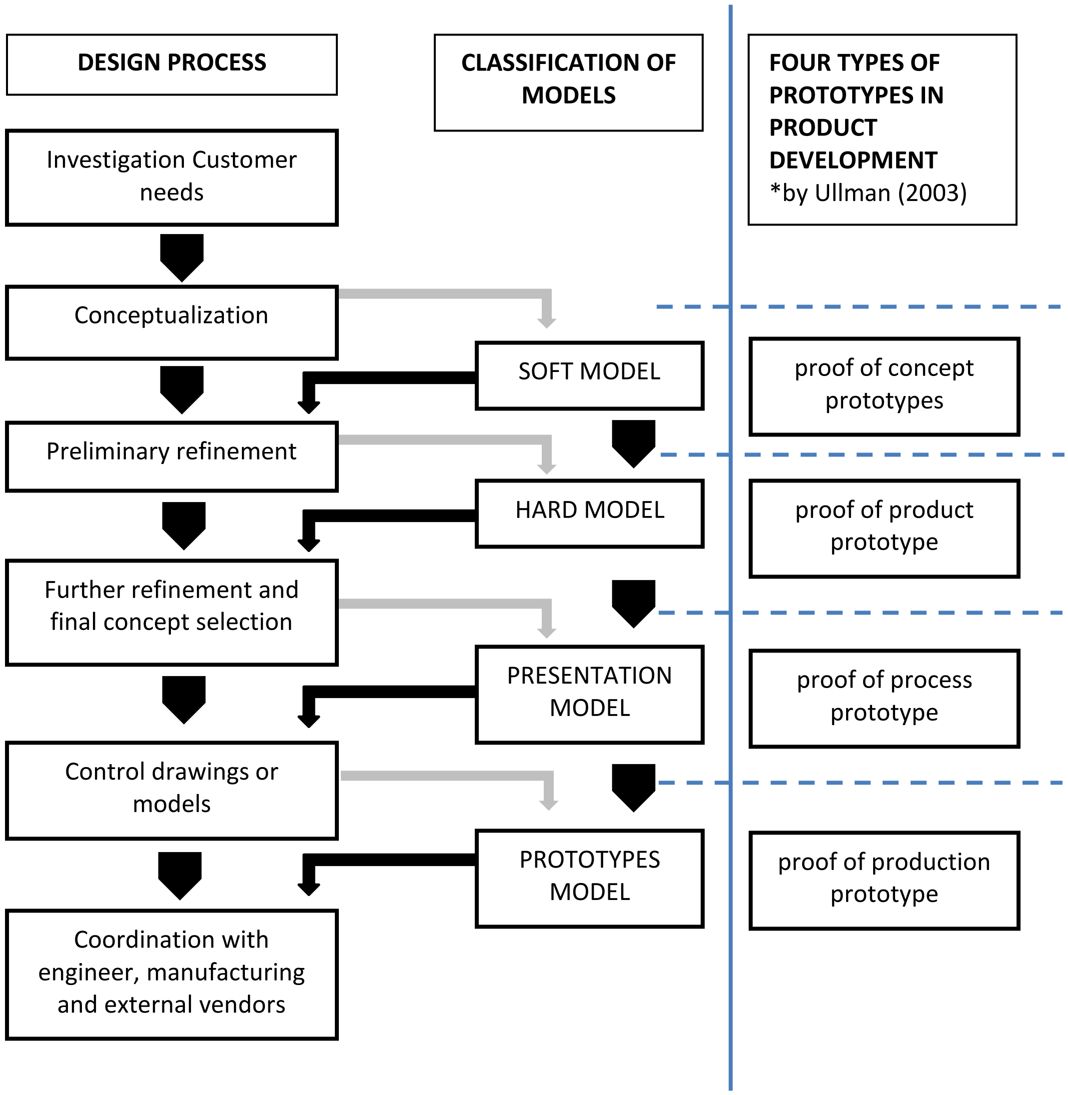


Figure 4: sample of prototypes. (Source from Terstiege, 2009)

4. Model making and prototyping with respect to the various stages of the design process

In design processes, models and prototype are produced to answer questions, which arise during critiques. Broek, et al. (2009) claims that models and prototypes can help designers to manage their design process more effectively. Physical models are also indispensable for designers to experiences shape, shape detailing, shape composition and functionality. According to Ulrich and Eppinger (2012), the prototype classification of Ullman (2003) and other researchers will be used to represent design ideas, concepts and solutions at various stages of the design process as shown in Figure 5.

Figure 5: The linkage of models and prototypes with the different stages of the design process according to Ullman (2003) and other researchers (Adapted from Ulrich & Eppinger, 2012)



By making physical model during the early design stages can help designers to visualise and solve complex product and system design problems. For example in the early conceptualization stages of the design process, soft 3-D models complement the ambiguity of 2-D sketches and drawings. Coherently with the creative development of the design concept, the qualities of accompanying models are also expected to improve up to the level of a "hard model". This hard model will then be used in the detailing and materialisation stages of the design process to refine the selected design concept according to specifications as earlier stated in the project. Final prototypes are instrumental for assisting designers and engineers in the engineering development phases to confirm the design for manufacturing and assembly. However, it should also be mentioned that the final prototype is not the end result of a design process. Instead, Computer-aided design (CAD) models or engineering drawings are considered to be final outcome of the design process, as it will be the medium for design transfer and communication between designers and engineers.

Broek, et al. (2009) clearly stated that design processes will depend on, but also influence the complexity of the design task. From an explorative design perspective, early stage physical model are built to answer designers' questions concerning overall shape, volume and proportions as efficiently and effectively as possible. Early in the design stage process, designers tend to develop as many soft models as possible to evaluate concepts as fast as possible, because of time and financial constraints. (Ulrich and Eppinger, 2012). However, these soft models should be accurately and geometrically well-defined to assess the alternative design solutions at the "Conceptualisation" and "Preliminary Refinement" stages of the design process (see figure 5). As designers tend to choose the fastest and cheapest material, such as foam and core board for early model making, which are low fidelity and it is quite difficult to present and represent a high level of detailing through these low-fidelity models (Hallgrimsson, 2012). Different from the conceptual design stage where everything is subject to significant changes, designers adopt high fidelity models to represent accuracy and confirm the ergonomic and aesthetics functionality of the design according to specifications in the final stages of the process. Here, the models are usually made from wood, dense foam, plastic or metal that show exact finishing and some functionality (Hallgrimsson, 2012).

According to Ullman´s (2003, p.651) earlier mentioned classification of prototypes; (1) proof of concept prototypes are used in the early stage of product development, (2) proof of product prototype clarifies a designers´ physical embodiment and production feasibility, (3) proof of process prototype shows that the production approaches and resources can successfully result in the preferred product, and (4) finally a prototype demonstrates that a complete manufacturing process is effective in proof of production. However, Ullman´s classification of prototypes in the design development process, as shown in Figure 5, is developed to assist designer to evaluate designs on user-functionality.

Table 2 provides an overview of how physical models are classified according to type and usage. (Ulrich & Eppinger, 2012), (Kimoji and Tano, 1991), (Viswanathan & Linsey 2009), (Mascitelli 2000), (Broek et. al, 2009), (Hallgrimsson, 2012). By viewing the classification according to usage we can analyse the relationship among them. Table 2 shows how three physical models are being assessed according to different criteria for designing activities. Each of the models has their own strengths and weaknesses with respect to how they are being applied in and contributes to the design process. (Broek et. al, 2009)

As a designer it is essential to be aware of the qualities of different models and prototypes and understand how they can be applied in designing new products, before decisions are made to proceed with producing the product. As emphasised by Broek et. al, (2009) every physical model used in conceptual design development have a different purpose compared to those applied in the detail design stages. The differences are shown in table 2. However, models that are supporting both the conceptualisation and detailing stages of the design process should be able to demonstrate the qualities of the design and design concepts, such as form, ergonomic functionality, technical functionality, complexity volume and price. Moreover, designers also need to consider criteria for the prototyping and modelmaking process itself, especially with respect to reasonable lead times and resources for producing the models at various stages of the process.

Table 2: Classifications of physical model according to usage

Types / Usage	**Soft Model** (Ulrich &Eppinger, 2012)	**Hard Model** (Ulrich &Eppinger, 2012)	**Prototype** (Ulrich &Eppinger, 2012)
Visualization (Broek et. al, 2009)	● Visualization tool for early insights (Masctelli, 2000)	● Support about shape, function, geometry, colour and product appearance can be judged (Broek et. al, 2009)	● CAD , detail design stage , PCM, very detailed model (Broek et. al, 2009)
Functionality testing (Broek et. al, 2009)	● Cannot be tested with actual usage , not functional ● Depending on the tested function ● Not using the same material (Broek et. al, 2009)	● Can be tested with actual size but with not full function criteria ● Depending on the tested function ● Not using the same material (Broek et. al, 2009)	● Final trade-off of performances (Masctelli, 2000)
Physical testing (Broek et. al, 2009)	● Cannot be tested with actual usage , not functional ● Depending on the tested function ● Not using the actual material (Broek et. al, 2009)	● Can be tested with actual size but with not full function criteria ● Depending on the tested function ● Not using the actual material (Broek et. al, 2009)	● correct interpretation of ergonomic data or of good practice in the measurement of individual subjects. (Broek et. al, 2009)
Marketing (Broek et. al, 2009)	● product appearance can be judged (Broek et. al, 2009) ● Incorporate early feedback from customers (Masctelli, 2000)	● product appearance can be judged (Broek et. al, 2009)	● Express the added design value of product to outsiders ● Results in higher user satisfaction (Broek et. al, 2009)
Proof of concept (Broek et. al, 2009)	● Initial early stage model (Ulrich &Eppinger, 2012)	● Semi detail model (Ulrich &Eppinger, 2012)	● A very detail model in the final stage of design to qualify the product design against requirements. (Broek et. al, 2009)
Editing (Broek et. al, 2009)	● When needed decomposed again and rebuild with different shape (Broek et. al, 2009)	● Editable models are assembled or composed model (Broek et. al, 2009)	● Not editable and will lead to higher cost (Broek et. al, 2009)
Technology (Broek et. al, 2009)	● Not complex technology and manual handmade (Broek et. al, 2009)	● Not complex technology and manual handmade ● Expose designers to potential future system enhancements (Broek et. al, 2009)	● Complexity technology of manufacturing ● Complex in terms of number of parts, shape (Broek et. al, 2009)
Communication (Broek et. al, 2009)	● Early communication with management and customers (Masctelli, 2000)	● Communication tools for gaining buy-in of executive management (Masctelli, 2000)	● Users expect the performance of the ultimate system to be the same as the prototype (Broek et. al, 2009)

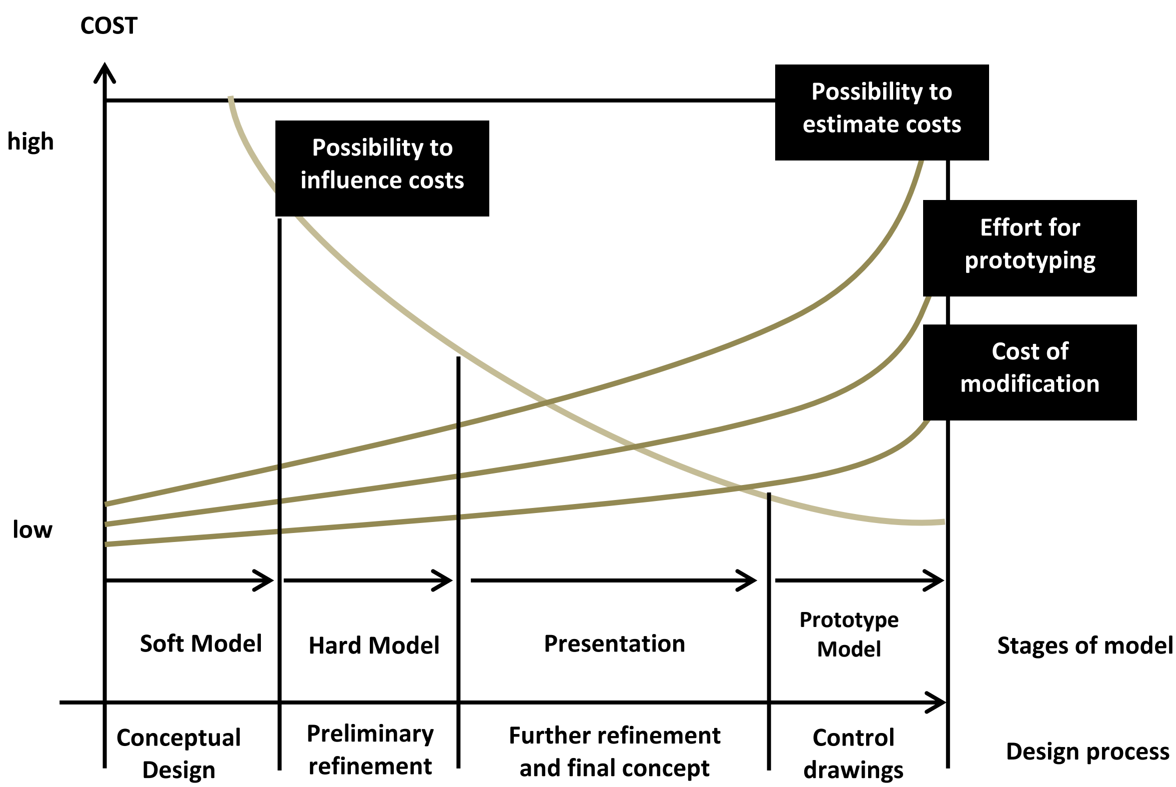
5. Conventional model making versus rapid prototyping on design and development practice

5.1 Creative and cost-efficient approaches in generating design solutions through models and prototypes

Ehrlenspiel, et al (2007) mentioned that costs for making design changes are minimal in the beginning stages of the design process. However, modification costs and efforts may significantly and exponentially increase as the design progresses towards the final stages of the design process. Romer et al. (2001) added that traditional tools such as sketches and simple physical models are very useful and cost efficient in generating design solutions in early phase of design process. Stolterman and Tenenberg (2008, p.7) complements this view by stating that the primary strength of an early prototype is in its incompleteness. It is the incompleteness that makes it possible to examine an idea's qualities without building a copy of the final design. Prototypes are helpful as much in what they do not include as in what they do.

Figure 6 shows the possibilities of influencing costs in design process using physical model as a support tool in generating ideas. Here, designers should be aware of how these media predict design and development costs with respect to planned as well as unplanned modifications. It is recommended that designers should use holistic physical models extensively and as early as possible in order to plan the design process more accurately in terms of focal areas, expected user involvement and cost estimations for the final design as well as related prototyping and pre-production activities. Hereby the author underlines that the iterative use of soft models in the early design stages, highlights key design problems more thoroughly, and enlarges the creative space for generating design solutions in a more cost effective manner.

Figure 6: The possibilities costs of model making in relation of design process, adapted from Ehrlenspiel, et al. (2007)



5.2 Models and prototypes to facilitate usability

Avrahami and Hudson (2002) mentioned that design practise has gone through major changes in the last quarter of 20th century. One of the main changes was a focal shift to place the consumer, instead of the product, in the center of the design process. This approach, known as user-focused or user-centered design, requires that user needs, goals and desires are satisfied. In other words, user centered design is a process that involves users in designing, from the investigation of needs until the finalisation of the design. Within this framework of user-centered design, four key principles are emphasised: early focus on users and task, prototyping and user testing and iterative design. (Gould and Lewis 1985)

User–centered approaches in conjunction with the implementation of models and prototypes, whether virtual or physical, are often being adopted in the study and design of human computer interaction (HCI) products and interfaces. Referring to Mackay and Fayard (1997), Dijkstra-Erikson et al. (2001) Human Computer Interaction is a multi-disciplinary field, which combines the elements of science, engineering and design. According to Norman & Draper (1986) HCI is an important field, where explorations of the interactive system between users, and artefacts within a specific environment centers around the use of "prototypes". In comparison with Industrial design, prototyping in HCI is principally more embedded within the cognitive and analytical aspects of the designing activities. For example, models and prototypes are instrumental in the creation of user scenarios, allowing users to see and experience the system before it is realised. Underlined by Lafon and Mackay (2000), prototypes in a user centered design process help designers to explore real world scenario and to analyse user's needs.

5.3 Rapid prototyping on design and development

Although the new and rapid techniques for prototyping are being introduced more profoundly, conventional techniques of model making are still indispensable for the design industry (Verlinden, et al. 2003)

Rapid prototyping and virtual prototyping are one of the most recent methods of prototyping, which have been introduced in the late 1980s and are still developing rapidly, as more than 30 difference techniques of RP have been developed and commercialized. (Chua, Leong and Lim, 2010). Verlinden et al. (2003) stated that rapid prototyping can be referred to as a process, which create physical forms based on digital technology in an automated manner. They classified Rapid Prototyping under three categories: incremental, decremental and hybrid technologies. In incremental prototyping, the object is being built by adding material in a controlled manner so that a desired shape is formed, for example Stereolithography (SL) and Selective Laser Sintering (SLS). Decremental prototyping is a process, where material is being removed from a stock of raw material to create the desire object, for example CNC milling. An example of Hybrid technologies is Laminated Object Manufacturing (LOM), making use of a combination of decremental and incremental technologies, where layers are cut out of solid material and are then glued together (Verlinden et al., 2003, p.1).

Other scholars such as Chua and Leong (1997) classified RP in four primary areas which are "Input", "Method", "Material" and "Application". Burns (1993) categorised rapid prototyping under two difference process, which are additive and hybrid processes, while, Chua, et al. (2010) suggested an alternative way of classifying RP systems according to the initial consistency of the used material, which is liquid-based, solid-based and powder-based.

Campbell (2002) mentioned in his research that rapid prototyping methods are most suitable for explicitly showing usability, aesthetics and technical qualities of a design. RP methods are a fast and reasonably cost-effective alternative to the conventional methods of manufacturing of models and prototypes. The final model is an accurate representation of the actual product, which can be measure and evaluated in terms of ergonomics, aesthetics and technical functionality. Rapid Prototyping also helps to prospectively asses the possibilities for manufacturing through its close relationship with 3-D data. The preciseness of RP and CAD, may avoid designers making mistakes by overlooking unforeseen problems. However, there are other people who are of the opinion that rapid prototyping is not effective enough, because it fails in terms of repetition and duplication of the real product or system. (Verlinden, et al.,2003)

5. Discussion

According to Lim et al. (2008, p1) prototypes should not only be viewed as having a role in the evaluation of design solutions, they also have a generative role in enabling designers to reflect on their design activities and in exploring design spaces. This study has demonstrated that models and prototypes are indispensable representation tools for practicing designers. From the early stages of the design process, physical prototypes enhance designers´ creativity and insight to solve design problems, develop creative ideas and concepts and refine the final design as thorough as possible. Complementary, the extensive use of models and prototypes may also have positive influence on how design practitioners manage their design processes. The way they classify models and prototypes inherently determine the level of completeness of what should be delivered for each stage of the design process. In short, it helps the designer to set interim deadlines with clear targets.

From a presentation and communication perspective, it is essential that designers use models and prototypes to communicate their design with different stakeholders to gain a better understanding of their needs and interests. With respect to internal communication models and prototypes will assist in developing marketing, promotion and advertising campaigns, and helps to facilitate the back-end product develop process among design and manufacturing engineers. Concerning usability studies, models and prototypes may assist in soliciting passive or active participation from potential users and other stakeholders. In terms of active participation, where users and other stakeholders are involved in a co-creation process (Sanders and Stappers, 2008), more innovative designs may be generated through the discovery of hidden needs.

Models and prototypes can be instrumental in facilitating design changes without too much burdening the financial resources of an organisation. Based on the “Economic principle of prototyping”, the simplest and most efficient prototypes are the best ones, making it possible to foresee and measure opportunities and limitations of a design idea (Lim et al., 2008). This implies that the designer should take the effort to carefully plan and strategise the use models and prototypes to efficiently and effectively support decision making activities throughout the designing process. Hereby designers should be aware of the existing spectrum of models, which ranges from an incomplete to complete state. The challenge for the designer is to iteratively customise a balanced selection of models and prototypes, which support the design and initial back-end development processes in the most economical way.

6. Conclusion

Given the role in supporting design thinking problem solving and communication, physical models and prototypes facilitate designers´ practices at different stages of the design process. It also helps them to communicate their designs with different stakeholders where insights have to be acquired and decisions made.
From an economical perspective, models and prototypes are influential in determining when, how and to what extent design changes are allowed with respect to how far the design has progressed.

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