Chapter

Rapid Physical Models: A New Phase in Industrial Design

Peer M. Sathikh

Abstract

Rapid prototyping, especially in the form of 3D printing, has pervaded over key aspects of design engineering since the start of this millennium. Today, rapid physical model making has applications in engineering, architecture, design, and fine art. While 3D printing today is mostly about prototyping of design as a precursor to production, not many have studied the use of 3D for industrial design in detail. With core responsibilities for three important nodes of user experience, namely function, human factors (ergonomics) and the aesthetics and emotion, 3D printing has been playing a major role in the process of industrial design. This chapter elucidates this through examples leading the reader to think about the future practice of rapid physical model making in industrial design. The chapter concludes by mentioning future scenarios that industrial design may take with constant innovations in 3D printing.

Keywords: Industrial design, form and function, rapid physical models, 3D printing

1. Introduction

Industrial design as a profession started around 100 years ago, stemming from the fact that the end of the eighteenth century saw two developments which required an entirely different approach to products. Firstly, products were no longer 'artefacts' but products themselves. Secondly, the emergence of the concept of mass consumption which sounded the end of 'industrial art' which was more interested in the decorative elements of the product rather than the appropriate aesthetics for the product which considers both the function and form. According to the Conran Directory of Design [1], it was in 1910, in Germany, when an architect named **Peter Behrens** took complete charge of the all aspects of the appearance of an industrial corporation for AEG, designing everything from products such as table fans and electric kettles to posters to the interior design of the building itself (**Figure 1**)[1] that the first signs of industrial design as a profession.

With new materials and production methods emerging at the end of the 19th century, the thought of formalising design education programme, separate from arts and handicrafts, began to take shape in Europe. It is with the founding of the **Bauhaus** in Weimar, Germany in 1919 by **Walter Gropius**, that design as a profession for the modern world became recognised. Bauhaus in its short life spanned a design philosophy which still has influence today. On the other side of the Atlantic,

[1] Source–left: http://www.sothebys.com/en/auctions/ecatalogue/2007/deutscher-werkbund-to-bauhaus-an-important-collection-of-german-design-n08459/lot.46.html
Source–right: https://www.ft.com/content/a0d0b9b8-4245-11e8-97ce-ea0c2bf34a0b

Figure 1.
Industrial design for AEG by Peter Behrens.

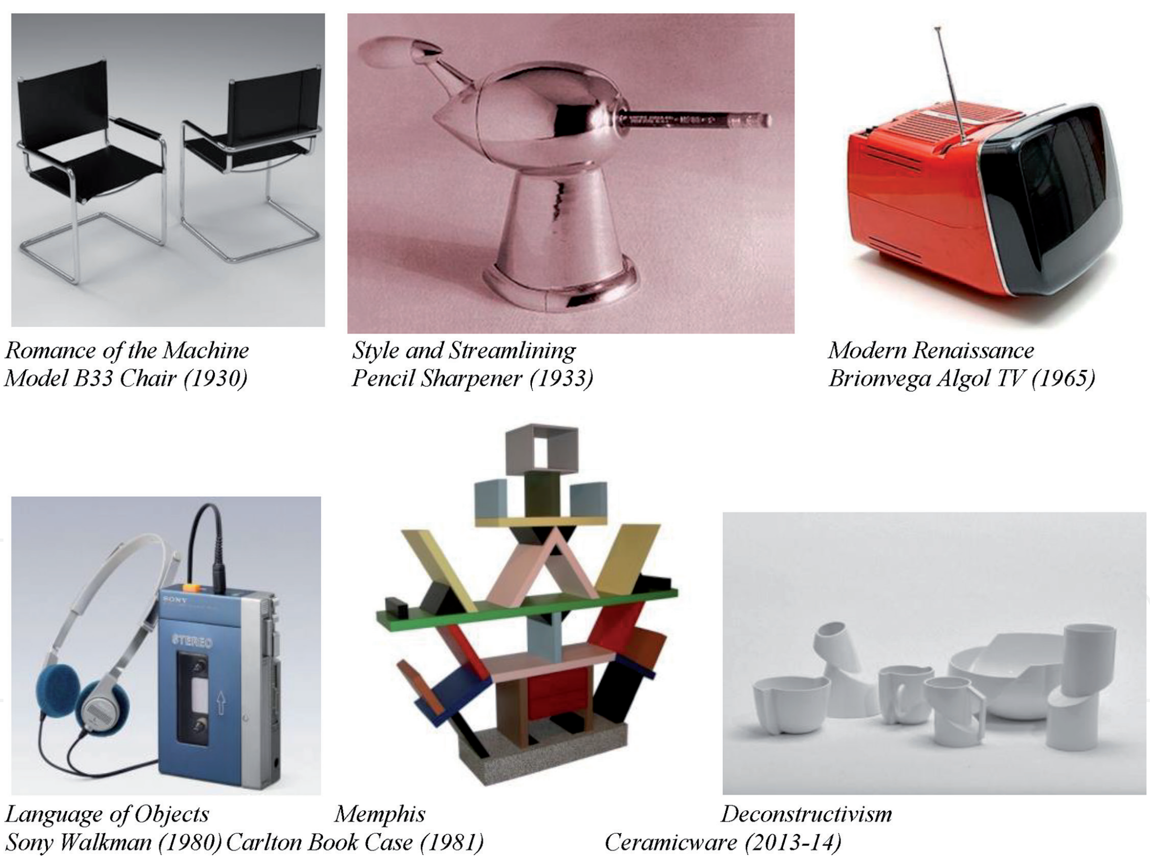

Figure 2.
Industrial design through different phases/movements.

several key players such as Norman Bel Geddes, Walter Dorwin Teague, Henry Dreyfuss, Harold Van Doren and **Raymond Lowey**, each from different background started plying their trade as consultant designers around the same time.

Industrial design, since then, has traversed through several phases, more or less following the progress of technology in varied fields, including materials and manufacturing, computer science & engineering and information technology to where it is today. According to Stephen Bayley, the editor of the Conran Directory of

Figure 3.
Lowey's redesign of Gestetner duplicator; first use of clay to model the form (source: https://collections.vam.ac.uk/item/O322014/gestetner-duplicator-duplicator-loewy-raymond-fernand/#).

Design [1], industrial design has passed through mass consumption (beginning of consumer age), the modern movement (the romance of the machine), the style era, modern renaissance, the language of objects (symbolism and consumer psychology) till the 1980s. Since then, the postmodern era has seen some radical design movements such as the Memphis and Deconstructivism. Significant and iconic products of each phase are seen in **Figure 2**.

The biggest effect of industrial design, right from its earliest beginnings, has been the use of physical models during the design process. Stephen Bayley [1] writes that, 'In his first major job, in 1929 for the English reprographic machine manufacturer Sigmund Gestetner (**Figure 3**), he fused the spirit of the times with 50 lbs of clay and made the first piece of office equipment to rely on streamlining'. Why did Lowey use clay? He himself explains that, 'And because Gestetner needed the design so quickly, there was no way to work in steel. I kept as close to the skeleton as possible to be efficient' [2]. Since then, physical models, to check not only the aesthetics, but also the ergonomics, function and dimensional fit of products, have been used extensively in industrial design.

2. Physical models in industrial design

Industrial designers have been using physical models in the design process in many ways. What started off as a means to portray form and aesthetics in a three-dimensional format, physical models have evolved to be used for many intentions and purposes during the different stages of design. Towards the mid-1980s, the design process was more stabilised with distinctive and accepted stages as ideas progressed through as shown by the simplified diagram in **Figure 4**.

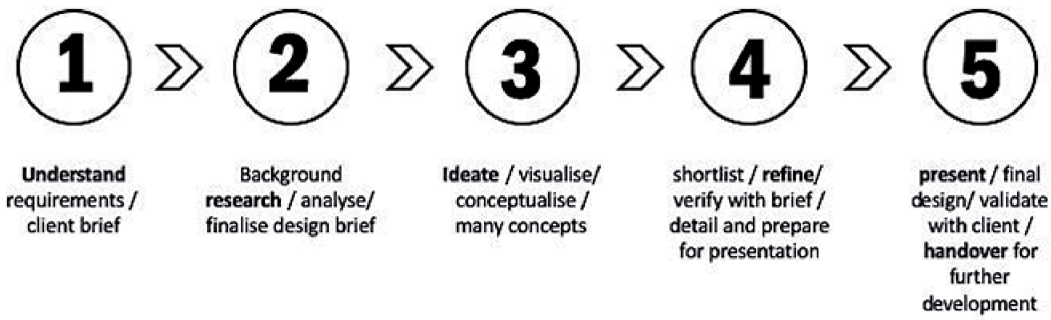

Figure 4.
Industrial design process.

Figure 5.
Study models (source: http://whiteboardps.com/index.php/fwp_portfolio/acco-swingline-gbc-fusion-laminators/).

2.1 Non-functional models

Referring to **Figure 4**, it is during stages 3 and 4 that physical models play a very important part in industrial design. During Stage 2, designers rely on sketching as an ideation tool. Traditionally, it was common (and still is) to produce concept sketches using pencil/ball pen/felt tip pen on paper generation concepts in freehand perspectives. While perspective drawings convey the form and shape of the product being conceptualised, not all people can interpret the sketches and understand the nuances of the design concept being represented in those sketches.

For that reason, industrial designers resort to fabricating study models in foam, clay, plaster or any other material to supplement the concept sketches (**Figure 5**). Many a times these study models are made in full scale for the client and/or potential users to get a feel of the size, form and fit as well as the design details.

When products such as a car is being designed, study models take on a new meaning. It is a common practice to sculpt full scale models of the exterior using clay. This allows for not only verification of the form and the subtle carvings on the surface, it also allows for making changes to these surface curves and details which can then be captured back into detail design. **Figure 6** shows the clay modelling facility of a car manufacturer.

According to the Modelling Manager at Ford,[2] a full-size clay model of a vehicle allows the designers and engineers to spot potential issues in both the interior and exterior of the vehicle which are not apparent on digital or small-scale models. With the advance reverse engineering technology available designers model the changes that necessary by hand and scan those changes back into the computer in order to capture it and integrate this into the main 3D data to integrate into the final design.

2 https://social.ford.com/en_US/story/ford-community/automotive-news/we-reveal-a-ford-automotive-design-secret.html

Figure 6.
Clay modelling in full scale (source: https://i.pinimg.com/originals/40/fa/22/40fa22a8d8120cceed06deeb030 2db12.jpg).

Figure 7.
Full scale mock up model.

Figure 8.
Mock up model of electric scooter (source: https://www.designideas.pics/porter/).

During Stage 4 of the design process shown in **Figure 4**, many times, full scale appearance model is presented to the client/audience which shows the exterior details in full including colour, texture and graphics as seen in **Figure 7**. It is a common practice to present more than one concept, hence more than one full scale mock up models are presented. In the case of vehicle/car design, scale models are presented as shown in **Figure 8**.

Figure 9.
Foam models to check form and ergonomic fits (source: https://www.pinterest.com/pin/289497082275373127/).

Figure 10.
Low fidelity mock up (source: https://engineeringproductdesign.com/).

Physical models in industrial design play a bigger role in design decision making than just iterating design/aesthetic variations including partially checking the function and fit of the product being designed.

2.2 Semi-functional models

At the early stages of the design process (Stage 2 in **Figure 4**), physical models play an important role in ascertaining human factors/ergonomics aspects of the product, besides presenting the form and fit. An example is shown in **Figure 9** where the ergonomics of a hand held power tool is important to the success of the product. Variations in the hand hold areas allow potential users to test/play act and give feedback on the right design for such areas.

In designing products with electronic displays and interface, it is a common practice to embed such components into the full scale mock-ups, many a times with

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Figure 11.
Quick furniture model.

rudimentary connections, to enable users to test the first level comfort in user experience. Such a mock up model as shown in **Figure 10** is also termed as' low fidelity' mock up in the industry. A low fidelity mock up allows the design team to verify the functional concept by allowing users to 'playact' the way they probably will use the real product. Designers can quickly make changes to the model based on feedback and make modifications. The almost real-time iteration of the design, allowing for variations in functionality make low-fidelity models an important part of industrial design in the age of interaction design.

Furniture designers use quick physical models to verify the concept in terms of aesthetics, manufacturing process and human fits. Such a quick model made by a student of furniture design is shown in **Figure 11**.

3. Classifying physical models

Physical models in product development in general, and industrial design in specific, may be classified in several ways. It is best to understand these classifications in order to understand the impact of digitalization and rapid model making has on industrial design.

Broek et al. [3] classify and exactly describe physical models according to usage and type as:

1. *Visualisation*: models are used for presentations and shape (details). They can support reasoning about shape geometry, curvature and accuracy, texture, colour, finishing, and graphics. Shapes become tangible, local curvature and product appearance can be judged.

2. *Functionality testing*: depending on the tested functions, the model representation is not too precise at those regions where no testing is performed. However, the degrees of freedom for optimal testing must be guaranteed, and testing regions, e.g., ergonomic verification, must be represented accurately.

3. *Physical testing*: a materialised model must be fabricated consisting of the same material of the final product. Accuracy and exclusion of strength variations related to the fabrication technology are important issues.

Soft Model	Hard Model	Presentation Model	Prototype
• rough modelling • use to assess the overall size, proportion, and shape of many proposed concept. • 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 • 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 • 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.

Table 1.
Classification of physical models [4].

4. *Marketing*: a marketing model or presentation model will express the added design value of the product to outsiders of the design process. The finishing quality and being a look-alike of the final product are crucial for this type of models.

5. *Proof-of-concept*: a very detailed model made in the final stage of design to qualify the product design against the requirements.

6. *Editing*: editable models are assembled or composed models and, when needed, decomposed again and rebuild with different (shape) components to create an adapted version of the same model.

7. *Communication*: a communication model is applicable for communication with the inside of the design process or for explanation to the related authorities to provide them with a better understanding what is going on in the design process.

8. *Process*: a process model is a kind of proto-model or protoshape like a CAD design or a physical model, which is treated in a reverse engineering way. In those models the progress of a design is captured, and the shape of a model can be change manually [3].

Of the classification by Broek et al. [3], classic industrial design is interested in *visualisation*, *functionality-testing*, *marketing*, and *proof-of-concept* models. Isa and Liem [4] state that there are, '… very limited classifications which clearly explained the actual characteristics and functions of each physical models in the design process' and that the lack of classifications makes it, '… harder for the designer to understand the true potential of physical models in various fields'. Isa and Liem [4] give a first level classification as shown in **Table 1**.

Isa and Liem [4] have also elaborated on the classification from Broek [3] which is shown in **Table 2**.[3] What **Tables 1** and **2** show are where the practice of physical model making in the design process has arrived at in the first part of the 21st century. This has been made possible through several key factors along the way. It

[3] Isa and Liem [4] have included Technology and have excluded Editing in the classification shown in **Table 2**. The references cited in **Table 2** refers to the source article [4].

Types / Usage	Soft Model [Ulrich and Eppinger 2012]	Hard Model [Ulrich and Eppinger 2012]	Presentation Model [Kimoji and Tano 1991]	Prototype [Ulrich and Eppinger 2012]
Visualization [Broek et al. 2009]	• Visualization tool for early insights [Masctelli 2000]	• Support about shape, function, geometry, colour [Broek et al. 2009]	• Represent outer appearance of the design, visualisation of total design [Broek et al. 2009]	• CAD , detail design stage , very detailed model [Broek et al. 2009]
Functionality testing *(Ergonomic Testing)* [Broek et al. 2009]	• Cannot be tested with actual usage, not functional [Broek et al. 2009]	• Can be tested with actual size but with not full function criteria [Broek et al. 2009]	• Some part of the design can be fully tested. [Broek et al. 2009]	• correct interpretation of ergonomic data or of good practice in the measurement of individual subjects. [Broek et al. 2009]
Physical testing [Broek et al. 2009]	• Depending on the tested function [Broek et al. 2009] • Principal testing [Sæter et al. 2012]	• Depending on the tested function [Broek et al. 2009] • Form and shape testing [Sæter et al. 2012]	• Can stimulate certain behaviour like strength and stiffness. [Broek et al. 2009]	• Final trade-off of performances [Masctelli 2000] • Fully functional model [Sæter et al. 2012]
Marketing [Broek et al. 2009]	• product appearance can be judged [Broek et al. 2009]	• Incorporate early feedback from customers [Masctelli 2000]	• Express the added design value of product to outsiders [Broek et al. 2009]	• Results in higher user satisfaction [Broek et al. 2009]
Proof of concept [Broek et al. 2009]	• Initial early stage model [Ulrich and Eppinger 2012] • Basic model [Sæter et al. 2012]	• Semi detail model [Ulrich and Eppinger 2012] • Complex shape [Sæter et al. 2012]	• Completely finished :color, gloss, texture etc. [Broek et al. 2009] • exact feel and look [Sæter et al. 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]	• decomposed again, rebuild with different shape [Broek et al. 2009] • lots of modification [Sæter et al. 2012]	• When needed decomposed again and rebuild with different material and adjustment of the shape. [Broek et al. 2009]	• Editable models are assembled or final composed model [Broek et al. 2009]	• Not editable and will lead to higher cost [Broek et al. 2009] • Very minor adjustments [Sæter et al. 2012]
Technology [Broek et al. 2009]	• Very inexpensive and quick [Lafon and Mackav management and customers [Masctelli 2000]	• Not complex technology and manual handmade [Broek et al. 2009] management [Masctelli 2000]	• Expose designers to potential future system enhancements [Broek et al. 2009] developers and end users. [Lafon and Mackay 2000]	• Complexity technology of manufacturing, complex in terms of the same as the prototype [Broek et al. 2009]

Table 2.
Classification of physical models according to usage [4].

is important to understand what has changed from 100 years ago as summarised in **Table 3** showing the progress based on the materials and the method of fabrication/manufacture of the physical models. It can be seen from **Table 3** that, as the method of fabrication of physical models progressed from hand fabricated models to automated model making, the accuracy of the dimensions and the ability to

	Hand Fabrication	Basic Machine Based	NC Machine Tools	CNC Machine Tools	High Speed CNC	Laser Cutter	1st Generation 3D Printing	2nd Generation 3D Printing	3rd Generation 3D Printing
Clay	●				●				
Plaster	●	●							
Foam	●	●	●	●					
Polystyrene		●	●	●					
ABS		●	●	●	●				
Acrylic		●	●	●		●			
MDF Board		●	●	●		●			
Chemical Wood		●	●	●	●				
Resin							●		
Filament							●	●	●
	Traditional				Rapid Models				

Table 3.
Progress of physical model making for industrial design.

realise models of complex/sophisticated form is increased. This shift from simple methods to complex process in model making has been accompanied by technological advancement, mainly in computer aided design (CAD) and computer numerical control (CNC) which are the keys to today's model making techniques such as high speed CNC, laser cutting and 3D printing. The availability of accurate 3D data produced by CAD software enables reliable CNC. According to Mike Lynch,[4] Founder and President of CNC Concepts Inc., CNC offers three distinct benefits, the first being the **reduced skill level** due to improved automation. The second benefit is the **consistency and accuracy** of the parts that are produced and third benefit is the **flexibility** to change to many different parts or models.

During the starting period of model making during the last century, the emphasis laid on the skill of the model maker. Those who took up this profession were craftsmen or, many a times, the designers. The dimensional accuracy of the model.

as well as the shape, form and finishes depended on the skill level of the model maker. With the advent of 'rapid' methods this skill was embedded in the machine and method itself and the model maker has more of a technician's role in the model making process. How did this change happen? This is best explained in the next section on computer aided design (CAD).

3.1 Enter CAD

The most significant progress in product design and development occurred with the advent of computer aided design (CAD) in the 1960s. CAD as an idea and working prototype was derived from the idea of CNC (which was developed by Dr. Patrick J. Hanratty in 1957) and first developed by Ivan Sutherland at MIT as SKETCHPAD which showed the capabilities of computers with display in technical drawing. The full potential of CAD as a three-dimensional development tool was realised through

[4] https://www.mmsonline.com/articles/key-cnc-concept-1the-fundamentals-of-cnc

Figure 12.
CAD sketching (source: surfaced.com).

software such as Pro/Engineer, UniGraphics, CATIA in the 1980s. With CAD, industrial designers were able to design in 3D and define the details on the surface and the various features within the 3D environment, which then becomes 3D data that is utilised by any CNC controlled system to machine or manufacture the design with a high level of fidelity in terms of dimensions and details. Today industrial designers use very sophisticated software such as Autodesk 360 and Rhinoceros, which allows for not only 3D data transfer for model making, but also for 'photo-realistic' renderings and to transfer the model to engineers for detail development. **Figure 12** shows the high level of flexibility that CAD offers including visualisation in sketch form which then could be automatically converted into 3D data.

Having 3D data that is transferrable with high reliability of the design concepts is the first step towards the realisation of rapid physical models. Many formats for transferring reliable 3D data have been developed, the most common ones being IGES, STEP, STL and OBJ. In the field of rapid model making, IGES and STEP are predominantly used in high speed CNC while STL and OBJ formats are the most reliable for 3D printing.[5] IGES is the earliest format and is still a popular, though more for 2D graphics and object rather than for 3D format. STEP is perhaps the first true 3D file convertor which relates to ISO 10303 and is widely used to transfer 3D data created by different CAD software platforms as well as transfer data to CNC programmers. STL is pure 3D information on geometry and shapes and does not hold any information colour, textures, etc. OBJ file format stores both form (geometry and shape) data as well as colour and texture information and is very useful in the latest multicolour 3D printers with high resolution capabilities.

4. Rapid physical models

Three distinct advances in machining technology has paved the way for rapid physical models in the last 25 years or so. At first, emergence of **high-speed CNC** milling machines in various sizes allowed model makers to fully utilise its capabilities for model making for industrial design.

Second is the emergence of two-dimensional computer-controlled **laser cutters**, which operate on the same drafting principle of a graphic plotter. This allowed for quick machining of 2D shapes in both opaque and transparent materials. It has been

[5] https://www.cadcrowd.com/blog/top-file-formats-for-sharing-3d-and-2d-cad-designs/

Figure 13.
Concept irons from students.

Figure 14.
3D printed spectacle frames (source: 3ders.org).

said that the famous Silicon Valley in California, USA, has overplayed the contribution of laser cutters in the development of hi-tech products.

Third, and the most influential technology in the development of rapid model making is introduction of additive manufacturing, which is also known as **3D printing**. 3D printing is not one technology but many that has been developed by several companies/corporation based on the principle that a model can be built, layer by layer, using materials that are deposited or extruded and cured to solid state as the layers are added. Looking at the history of 3D printing the first technology to emerge around 1984 was **Stereolithography** followed by Selective Laser Sintering (**SLS**) in 1988 which was then followed by Fusion Deposition Modelling (**FDM**). Several companies manufacture 3D printers in what is now a competitive market which cater to institutions and professional companies/outfit that could purchase and maintain a high-end rapid model making equipment. Since 2010, table top 3D printers that are much lower in cost and easy to maintain have become popular allowing not only designers, but craftspeople and hobby enthusiasts to purchase them.

4.1 Advantage of rapid physical modelling

The obvious advantage of rapid physical model making is in the saving of time and the human centric energy required to craft the models. This is especially so in the case of 3D printing where the need for assembling several fabricated parts to make a whole (model) is eliminated. This ability is more useful when early visualisation models that do not require finishes are made for form, fit and ergonomic testing.

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Desktop 3D printers and the economics it has brought also proves advantageous to students of industrial design, allowing them to make several iterations and variations of concepts within a short period of time allowing them the opportunity to explore options and discuss the pros and cons with the instructors before deciding on a final design. This option was mostly available as two-dimensional sketch and render exploration in the pre 3D printing era. **Figure 13** shows the result of two such student exercise where the final designs were 3D printed and finished with colour and details after preliminary models were printed for exploration.

Such an advantage of design exploration is also possible by professional designers and design companies, who have gone beyond the polished renderings to study and refine the overall design of the products due to the affordance that 3D printing offers. **Figure 14** shows 3D printed exploration and production spectacle frames.

The end result of such explorations seems to point to a new phase in industrial design where the traditional design process has been disrupted by CAD and rapid physical models. New concepts such as collaborative design has brought in real time design and development through networked connectivity and the Internet. As the profession of industrial design has done in the last century, it is evolving to meet this change.

5. The new phase in industrial design

With CAD, the Internet, networking, cloud computing, and rapid physical model making (as well as prototyping) engulfing the day-to-day activities of an industrial designer, what then could be the new phase of industrial design. These are some of the aspects of design and process that has changed:

a. **Change in the process flow:** The traditional approach to design process depict in **Figure 4** gives way to more multi-disciplinary process as shown in **Figure 15**. With 3D data being created, refined and evolved at the early stage of industrial design (Stage 3), first level development engineers can start working on the preliminary part of the development supported by rapid physical models that could be ‘shelled’ to leave void space. What was already possible with the introduction of CAD becomes much more concrete with the aid of such models that serve as low fidelity engineering prototypes.

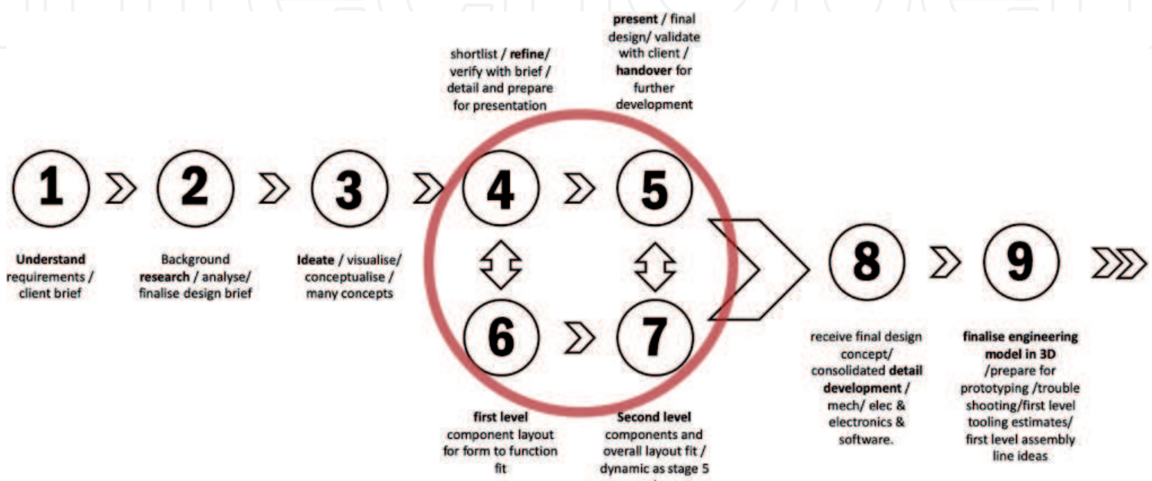

Figure 15.
Revised design process.

b. **Verification of industrial design details:** Photorealistic renderings are 2D depiction, either on the screen or on printed copies. This does not allow designers to look and feel the nuanced details and curves that form the surface of the product being designed. Rapid physical models allow for making several concepts for the same details and allow for study and discussion before a decision is made. In many cases another set of rapid physical models are built after modification for further checking. This is very true in the automotive industry where the body surfaces have subtle and nuanced curves and details. Waiting for a full-scale clay model may be too late and opportunities to make several variations get lost. **Figure 16** shows a high-speed CNC machining of automotive body in progress.

c. **Rapid physical models made simultaneously:** Since rapid physical models are made from a 3D data base created by industrial designers (and development engineers), it is possible to send the data across the world to any part of the world that has rapid model making facilities. This would allow for designers across the different places to inspect the model simultaneously and initiate variations that may be needed for the product due to various reasons, including cultural, environmental, statutory requirements or availability of components, etc.

d. **Localised manufacture:** The speed at which 3D printing technology is developing, allows for localised manufacture of products where the quantity is low, suitable for small batch manufacture. This will be a scenario where, for instance, medical support team has to build basic equipment and furniture, and perhaps shelters. Low cost, desktop 3D powered by batteries could be a solution for fabricating them to suit the environment and the environment. This idea could be extended to future manned missions to the Moon and Mars where industrial design and development work can be done on Earth and the data sent remotely for the mission personnel to manufacture and commission on sight.

e. **Small quantity and customised manufacture:** This is already a practice in the fashion accessories industry where designers' custom design jewellery and accessories are produced on a small scale, finished, packaged and distributed/sold. Spectacle frames are already being manufactured by laser sintered method in titanium as seen in **Figure 14**. This may be extended to interior decors/decals and fittings that do not have to take weight and load.

Figure 16.
High-speed CNC machining of car body (source: cnc-modelle.com).

f. **Others:** With rapid physical model making moving well ahead of the initial curiosity, it could be left to the creativity of future designers, engineers and business people to derive further uses for rapid physical model making to suit the demands of the word.

6. Summary and conclusions

This chapter gives a historical background to physical model making in the profession of industrial design right from the last decades of the 19th century through the foundation and development of industrial design during the 20th century till the first two decades of the 21st century. Alongside the history, the different types of physical models, together with the reasons for using each type was explained before touching on the research and development of rapid physical model making technologies, specifically high-speed CNC, laser cutting and 3D printers. Examples of how they are used has also been given in this chapter before the author moves on to discuss on how rapid physical model making is taking the profession of industrial design to its next phase of progress.

What this chapter presents is an overview of the importance of physical model making and the role it has played before moving on to how rapid physical models are setting the scene for the future of industrial design, all within the context of the other chapters in this book.

Industrial design has played a major role in the modern and postmodern era, by bringing a harmonious relationship between form, function and aesthetics in the built environment and life style over the last 100 years. With the Earth facing imminent danger to its natural sustainability, it is hoped that the profession will take advantage of the technological advances brought about by CAD, rapid physical model making and its development in sustainable materials together with high speed connectivity to influence the direction of human habitat on this planet in the near future, and perhaps other celestial bodies in the future to come.

Author details

Peer M. Sathikh
School of Art, Design and Media, Nanyang Technological University, Singapore

*Address all correspondence to: peersathikh@ntu.edu.sg

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