Software tools for Rapid Prototype as Design

A. Withell, O. Diegel, S. Reay
Auckland University of Technology, Centre for Rapid Product Development, Auckland, New Zealand

ABSTRACT: Design teams are expected to produce physical prototypes that demonstrate the working principles of their designs. These projects may involve multiple areas of technology, such as industrial design, electronics, mechanical engineering, software, and even marketing. The integration of physical, three-dimensional prototypes into the new product development (NPD) process, i.e. 'Prototype as Design' is an effective way to evaluate form, ideas, testing function, and for optimising products for intended users. The advent of the latest additive manufacturing and CAD/CAM technologies has transformed this process into a 'Rapid Prototype as Design' (RPaD) methodology. This paper describes the RPaD methodology and presents a case study of student product design projects, in which RPaD was used as a key design methodology. It also presents a software 'toolbox' that is used as a tool to facilitate the process, and use of the toolbox is demonstrated in the case studies.

1. INTRODUCTION

A prototype is an early model built to test an idea or product so that it can be learned from. Prototyping is one of the oldest product development techniques and has been used by artisans for centuries. Artisans created prototypes of their ideas, to ensure that they worked, before making the planned primary artefact. Prototyping falls into a number of different types, ranging from proof-of-principle prototypes, to demonstrate some mechanical principle or basic idea, to form study prototypes, used to explore shapes and aesthetics, to user-experience and ergonomic prototypes, to test principles from a user perspective, to functional models, to explore aspects of a product from a functional point of view. Many of these prototyping methods can take both virtual and physical forms in which an idea might be tested on paper, or on a computer, all the way through to different levels of physical models, ranging from simple card or foam models, to elaborate CNC machined or rapid-prototyped models.

The integration of physical, three-dimensional prototypes into the new product development (NPD) process, i.e. 'Prototype as Design' has always been an essential and effective way for evaluating form, ideas, testing function of individual parts and for optimising products for intended users. It is, for example, often impossible to precisely specify functional and user requirements at the front end of the NPD process. According to Mulenburg (2004), even if possible, it may be undesirable to do so. Further to this Singh & Vijayaraghavan (2001)], go on to discuss that this often makes a strategy where the use of 'prototype as a design' critical for success, as it is a highly interactive, integrated process that allows multiple iterations of complex aspects of a product to be quickly evaluated and adapted into a functioning whole.

Physical prototypes play an essential role in NPD as they are a means of demonstrating function, scale and realism in a way that paper drawings and CAD models cannot. According to Broek, Sleijffers, Horvath, & Lennings (2000), the translation from two dimensional to three dimensional representations is a key stage in NPD. The progression of prototypes can be seen as going from two dimensional to three dimensional on-screen, to three dimensional physical models. However there are large differences in perception between a user seeing a CAD model and then seeing and, possibly more importantly, feeling a real physical working model. According to Krar and Gill (2003), the additional tactile, haptic and true three-dimensional perception produces two completely different responses in the user.

Prototypes are also useful in producing one-of-a-kind projects by eliminating some of the formality of the traditional 'stage-gate' engineering design processes. This philosophy has led to the development of a design methodology referred to as 'Prototype as Design'. The traditional Prototype as Design technique, as used by the NASA's Ames

Research Center (Mulenburg, 2004), is very useful in creating unique, one-of-a-kind research hardware for small, high-risk projects. It is a methodology that encourages a much more parallel design process than can sometimes be achieved with conventional stage-gate techniques (Fig 1).

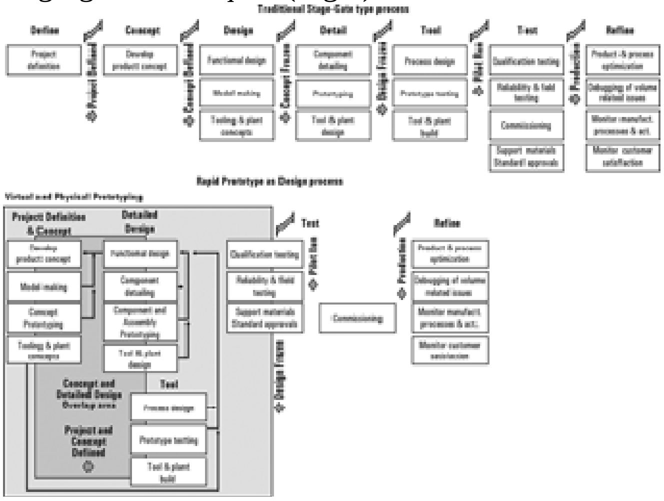


Figure 1: Comparison of Traditional and RPaD Processes

Where this methodology differentiates from conventional prototyping is that the final product is, in fact, still seen as a prototype, that has been created through a number of preliminary prototype stages. Though the Ames Research Center uses the methodology for one-of-a-kind products, many eventually mass-manufactured products can be thought of as a one-of-a-kind product during their development process. This, with the addition of a manufacturing consideration filter, can prove to be an effective technique for developing conventional products faster, and with results that can better satisfy user needs.

With the increasingly complex nature of contemporary products, and the sophisticated expectations of buyers and users, the use of ‘prototype as design’ to optimize products during the design process is becoming ever more important. The advent of the latest rapid prototyping, computer aided engineering (CAE) and manufacturing (CAM) technologies has added a new dimension to the traditional ‘Prototype as Design’ methodology. The new generation of software and hardware tools now allows engineers to perform complex finite element analysis (FEA) on their products, to test for interference problems and thermal or structural problems, or to simulate how plastic may flow through an injection molding tool during manufacturing. It is now evolving into a ‘Rapid Prototype as Design’ methodology.

2. RAPID PROTOTYPE AS DESIGN

The overall generic design process can now be described as follows: Initial conceptual sketches are still usually undertaken in 2D, both on paper and on the computer. More advanced conceptual design and engineering design models are then usually produced using 3D CAD software. This produces a virtual model that can be rotated, zoomed in on, measured and manipulated on-screen. From this 3D computer model, a physical rapid prototype can be produced. Traditionally, the only way to produce a real, physical model was to either use a subtractive technology such as Computer Numerically Controlled (CNC) machining or to produce expensive tooling into which the part could be injection molded. Both these methods can be time consuming and expensive.

The latest generation of rapid prototyping technologies such as stereolithography (SLA), Selective Laser Sintering and Melting (SLS/SLM), Fused Deposition Modelling (FDM) and 3D printing now allow physical prototypes to be produced within hours rather than days (Chua & Leong, 2003).

The rapid prototyping process begins by taking a 3D computer generated file and slicing it into thin slices (commonly ranging from a few microns to 0.25mm per slice depending on the technology used). The rapid prototyping machine then builds the model one slice at a time, with each subsequent slice being built directly on the previous one (Wohlers, 2009). Chua and Leong (2003) present a good outline of how the technologies may differ for each method in terms of the materials they use to build the part, and the process used for creating each slice of the model.

Some of the rapid prototyping processes which, until recently, were only able to make plastic-like parts, are now producing metal parts in a variety of metals including aluminum, titanium, and stainless steel, and ceramics. Not only is the choice of materials and processes increasing, but the last few years have seen a significant reduction in the cost of these technologies. Systems are now also available for simulating the behaviour and performance of electronic circuits, and for rapid prototyping complex printed circuit boards (PCBs).

These technologies mean that it is now possible to construct highly advanced virtual prototypes, and then fully working physical prototypes, including mechanical hardware, software and electronics, almost as fast as they are designed, thus allowing many more iterations of a design within a shorter timeframe. This, in turn, allows for products that are even better suited to their intended users in even shorter times.

It is important to remember that a product prototype includes more than just its mechanical parts. Many products also include electronic and software components which must also be prototyped as part of the process. It is vital to understand that the mechanical, electronic and software systems are closely related to each other and that the design of one should therefore affect the others. This is why it is so important that all disciplines work as a single unit rather than as simple parallel activities. It is also vital to remember that the RPaD process, as described above, is not intended to be a linear or sequential process. This distinction can easily get lost when trying to describe a process on paper. To operate effectively, the RPaD process must operate as a parallel tasking project in which the prototyping happens in parallel to any, and all, stages of the process.

3. DESIGN METHODS TOOLBOX

To facilitate the use of RPaD, and a number of other design processes and tools, an online software package was created to allow students and practioners easy access to the tools as well as a range of examples and applications of the tools.

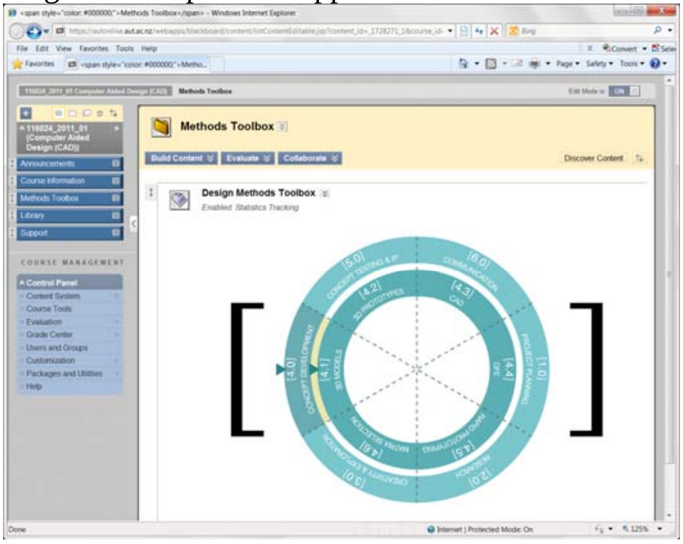


Figure 2: Front page of the Design Tools Online software

The 'Design Methods Toolbox' presents a conceptual model of a six stage, product design and development process (see fig 1.). Within each of the stages, six key design methods are presented (se fig. 2). The goal is to provide a resource that gives undergraduate product design students and practioners a simplified, but solid and practical framework for learning about, and applying the design process in their practical design work. The methods in the 'Design Methods Toolbox' are currently delivered to the students as part of the design studio teaching programme through lectures and practical 'hands-on' workshops, while the online version of the software gives them easy access to refresh themselves in the use of the methods.

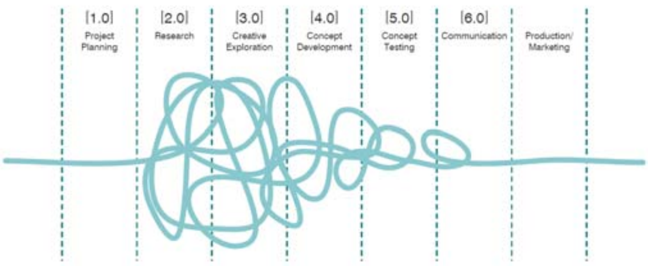


Figure 3: Conceptual model of the design process

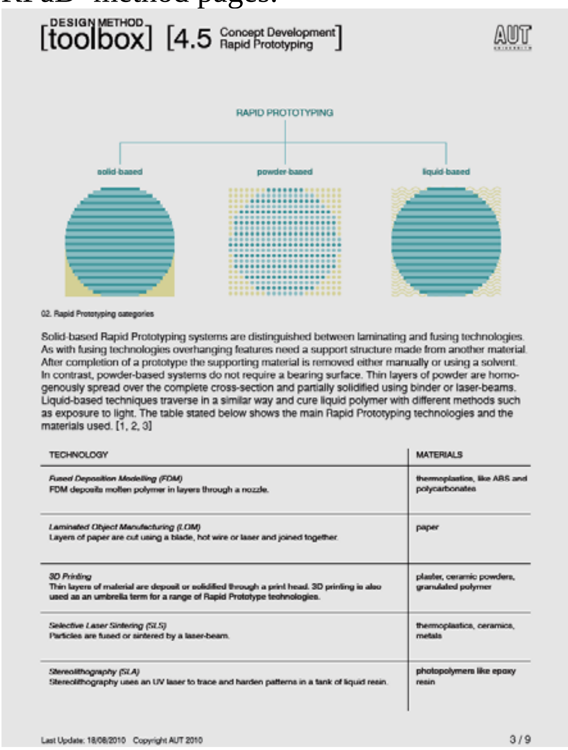
Table 1. Design methods provided by the toolbox

1.0 Project Planning	2.0 Research	3.0 Creativity & Exploration	4.0 Concept Development	5.0 Concept Testing	6.0 Communication
1.1 Design Process	2.1 Lit Review	3.2 Role Playing	4.1 3D Models	5.1 Task Analysis	6.1 Reports
1.2 Goal Setting	2.2 Survey	3.2 Mind Mapping	4.2 3D Prototypes	5.2 In Situ Placement	6.2 Story Boards
1.3 SWOT Analysis	2.3 Interviews	3.3 Brainstorming	4.3 Computer Aided Design (CAD)	5.3 CAD Simulation	6.3 Presentation Boards
1.4 Gantt Chats	2.4 Observation	3.4 Lotus Blossom	4.4 Design for the Environment (DFE)	5.4 Life Cycle Analysis (LCA)	6.4 Photography
1.5 PESTLE	2.5 Trends Analysis	3.5 Six Thinking Hats	4.5 Rapid Prototyping as Design	5.5 Product Costing	6.5 Moving Image
1.6 Project Brief	2.6 Personas	3.6 Concept Ideation	4.6 Matrix Selection	5.6 IP Protection	6.6 Reflective Practice

To give the students a good grounding in each design method the following is included:

1. Introduction and background to the method
2. Key steps in use the of the method
3. Examples based on 'best practices' by other students.
4. Variations – links to other related methods
5. References
6. Key links to more detailed resources and examples are provided for students independently further explore
7. Templates and/or other resources to aid in use.

For example the Rapid Prototyping as Design (RPaD) method is presented as a key part of the Concept Development phase of the product design and development process. The basic concepts of rapid prototyping are communicated through simple diagrams, each technology is then described, and most importantly examples of best practice student work are included. Figure 4 shows an example from the RPaD method pages.


DESIGN METHOD [toolbox] [4.5 Concept Development Rapid Prototyping]

AUT

RAPID PROTOTYPING

solid-based powder-based liquid-based

02. Rapid Prototyping categories

Solid-based Rapid Prototyping systems are distinguished between laminating and fusing technologies. As with fusing technologies overhanging features need a support structure made from another material. After completion of a prototype the supporting material is removed either manually or using a solvent. In contrast, powder-based systems do not require a bearing surface. Thin layers of powder are homogenously spread over the complete cross-section and partially solidified using binder or laser-beams. Liquid-based techniques traverse in a similar way and cure liquid polymer with different methods such as exposure to light. The table stated below shows the main Rapid Prototyping technologies and the materials used. [1, 2, 3]

TECHNOLOGY	MATERIALS
Fused Deposition Modelling (FDM) FDM deposits molten polymer in layers through a nozzle.	thermoplastics, like ABS and polycarbonates
Laminated Object Manufacturing (LOM) Layers of paper are cut using a blade, hot wire or laser and joined together.	paper
3D Printing Thin layers of material are deposit or solidified through a print head. 3D printing is also used as an umbrella term for a range of Rapid Prototype technologies.	plaster, ceramic powders, granulated polymer
Selective Laser Sintering (SLS) Particles are fused or sintered by a laser-beam.	thermoplastics, ceramics, metals
Stereolithography (SLA) Stereolithography uses an UV laser to trace and harden patterns in a tank of liquid resin.	photopolymers like epoxy resin

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Fig 4. Introduction Page

4. PRODUCT DESIGN AT AUT

The three-year undergraduate product design programme at AUT University is a relatively new programme, developed in 2007 and launched with the first intake of students in 2008. In 2011 the programme has 80 students across the three years and 8 postgraduate students. The programme is centred on project/problem-based learning in which students are given studio space to work in, and access to workshops and prototyping facilities. Over the three years of undergraduate study the students work through a number of projects ranging from short i.e. two week, to full semester i.e. twelve week projects. Expectations range from conceptual outcomes i.e. 'blue sky projects' through to product outcomes as close to realization as possible.

While the development of a new academic programme provides many organisational and operational challenges, it also presents a unique opportunity to develop new approaches to teaching and learning without the constraints of institutional history and tradition. An innovative pedagogical approach to product design is currently being developed in the product design programme at AUT that focuses on integrating emerging, contemporary design methodologies and processes. The concept of 'Rapid Prototype as Design' is seen as a key methodology for the product design programme.

5. INTEGRATING 'RAPID PROTOTYPE AS DESIGN'

Traditionally product design schools have focused on the specific use of drawing and CAD as the primary creative methodologies, and a model or prototype was something that was usually created at the end, not something generated throughout the process. Given the traditional use of design methodologies, it is essential for the successful integration of new methodologies such as 'Rapid Prototype as Design' to get student 'buy-in' and a 'culture change' away from the traditional approaches and to a more hands-on process, using quick, effective and many generations of prototypes to test and evaluate ideas. Students must also learn to understand and independently select the most appropriate prototyping methods for a given context.

To achieve this at AUT, a number of key strategies are used to teach and integrate RPaD into the programme. This includes the development and delivery of key lectures and discussions to engage students in a discourse around the broader issues of the use of prototyping, hands-on workshops with a variety of prototyping processes from low-tech to high-tech, case studies of professional projects, physical examples previous student's project outcomes, and the use of other resources such as videos, site visits and access to online resources.

To illustrate the use of RPaD at AUT, a number of successful case studies are presented.

6. CASE STUDIES

As part of their studio programme students were asked to design a set of medical products with the goal to meet/exceed the needs of intended key users and to improve the overall experience of using the product. The students had twelve weeks in which to design the product from research, initial ideas to proof-of-concept prototype and put on an exhibition and create a product plan and report.

In order to achieve this goal within such a tight time-frame, the students were advised to specifically use RPaD as the key design methodology. In addition the students were asked to use clearly identified prototyping methods that best suited their idea or concept context. In some case this was undertaken through virtual prototyping and the use of CAD models. With other students, relatively crude but quick card or foam mock-ups were used. When more complex ideas were being tested, students used laser cut or rapid prototyped models. They were strongly encouraged to use their prototypes as a way of thinking about the problems they needed to overcome to reach their project goals. Overall students utilised a very wide range of prototyping processes.

Figure 5: Examples of student prototypes used in the project.

5.1 Moon-Boot

The goal of this project was to design and develop an innovative moon-boot cast for people with broken ankles. The students first undertook a detailed analysis of key users and, from the information gathered, identified that current moon-boots were unwieldy and bigger than they needed to be for a large part of a user's convalescence. After brainstorming to generate a number of design concepts, most of which were quickly prototyped, they came to a final design for a modular moon-boot in which sections could be removed as the user progressed through their recover, thus making the user more comfortable and therefore more likely to recover faster.

From the start of the project, the students tested all of their concepts and ideas with prototypes. Relatively crude card prototypes where first used to visualize initial ideas, then after starting to virtually prototype in CAD and physically prototype in parallel, the students progressed to laser-cut polypropylene prototypes leading to final, 3D printed plastic prototypes produced on a Dimension FDM machine.

One of the challenges faced by the students was in learning to identify which method of prototyping was most effective in achieving the purposes of a particular challenge, be it communicating and idea or testing an engineering or manufacturing principle.

Figure 6: CAD Model and Prototype of Moon-Boot

The prototype moon-boot shown in figure 3 is comprised of a mix of plastic 3D printing and laser cutting and is a fully functional proof-of-concept model.

5.2 Ambulatory Blood Pressure Monitor

In this project an ambulatory blood pressure monitor was redesigned and improved. An ambulatory blood pressure monitor is a blood pressure monitor that is worn continuously by the patient for 24 hours and which takes readings at preset intervals. Current models are worn on the belt and have air pipes leading up to the cuff which is wrapped around the upper arm. This makes it difficult for patients to wear at night as the tubes get in the way, and can stress patients to the extent of affecting their blood pressure.

Figure 7: Prototype of Ambulatory Blood Pressure Monitor

After prototyping a number of different concepts, the team settled on a design in which the entire monitor was worn on the arm. The electronics and pump became an integral part of the cuff. One of the prototyping methods used by this particular team was in the reuse of existing components, a very useful prototyping method that often gets ignored. All internal components, pump, solenoid, circuit boards were reused from an existing blood pressure monitor. This reuse of components drastically shortened the teams' development time on the technology front, and relatively easily allowed them to construct a working prototype.

5.3 Respiratory Humidification System

This project was focused on a respiratory humidification system in conjunction with Fisher and Paykel Healthcare, a major NZ manufacturer of healthcare products. The student was asked to redesign an existing product based on the findings of extensive user research in hospitals. The focus was to improve the experience of both staff and patients and to create the next generation of the product. In this case the student also challenged the existing humidification technology and proposed an alternative and potentially radical method of both generating and recycling humid air.

The project involved prototypes in the form of early concept form studies in foam, through to working prototypes for the development and testing of systems to produce humidity. This involved setting up alternative methods for generating humidity, creating air flow and the testing and comparing of each of the methods. A number of presentations of the prototypes were made to the client and to users for feedback. Once the overall form factor was developed and the complete system designed, the final form was refined using CAD. This culminated in the production of a final rapid prototype using FDM technology for high level communication and display purposes.

Figure 5: Prototype of Respiratory Humidification System

7. CONCLUSIONS

As newer virtual and physical rapid prototyping technologies emerge, the way in which they are used to more effectively manage the NPD process must evolve in tandem. Further to this, the traditional NPD processes must evolve into Rapid New Product Development processes. The combination of rapid prototyping technologies, not only in the mechanical area, but also in the electronic and software areas can be used to reduce the product development cycle if they are used effectively. Not only can the project time be reduced, but more desirable products can often eventuate as more design iterations can be gone through, thus more closely meeting the needs of the users.

It is essential that design and engineering programmes also engage students with new and emerging design methodologies and processes such as RPaD, and that they are embedded deeply into programme curriculums.

This paper has presented how at AUT, the product design programme is integrating RPaD into the teaching and learning programme, and has showcased a number of student design projects that have utalised RPaD as the core design methodology. All student teams came up with innovative solutions which were not only optimised for the user's needs, but were also relatively easy to manufacture. Most of the teams created between twenty to thirty prototype iterations for their projects (ranging from crude cardboard and foam concept models, to CAD prototypes, to highly polished plastic or laser-cut final product prototypes), which allowed them to develop their ideas in an effective and efficient manner. As they prototyped every idea they had, the idea was automatically tested for validity through the prototype. The AUT students have demonstrated that RPaD, as an excellent emerging professional NPD methodology, can also be effectively utilised by design students to develop innovative, new products.

8. REFERENCES

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