Rapid Prototype as Design, an Effective Product Development Methodology

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ABSTRACT: Design teams are usually expected to produce physical prototypes that demonstrate the working principles of the products they are designing within tight time-frames. The use of true concurrent engineering and the 'rapid prototype as design' (RPaD) methodology, combined with the ability to effectively integrate the many existing and emerging virtual and physical rapid prototyping technologies into the development process increases the potential of producing new high technology products in shorter timeframes. The paper presents a case study of the Spengler Cardiovascular Lab, a complex project involving a variety of technologies, including electronic, physical, mechanical, and software prototyping. This product was developed by a collaborative team working concurrently in three countries, in less than five months through the tightly integrated use of RPaD, concurrent engineering and virtual and physical rapid prototyping that allowed for a fast reiterative design approach and a short product development cycle.

1 INTRODUCTION

Most New Product Development (NPD) projects require the production of physical artefacts that demonstrate the working principles of the product. Thy often involve the development of a one-of-a-kind piece of equipment or machinery and often involve multiple areas of technology, such as electronics, mechanical, software, manufacturing, etc. They are also characterized by having to produce results within relatively tight time-frames, as dictated by company or market requirements.

Rapid Prototyping (RP) has, in recent years, become ubiquitous in product development. When talked about in the context of product development, RP almost always refers to the additive manufacture of physical models of hardware. It should be remembered, however, that very few products contain only mechanical hardware. Most also contain software and electronics and, to make most effective use of RP technologies, both software and electronics should be integrated into the overall prototyping process and methodology.

Concurrent engineering is generally well suited to rapid product development as its parallel processes naturally tighten the product development cycle (Huang, 1999). It should be noted, however, that many current applications of concurrent engineering are not as concurrent as the name implies. It is often used with different disciplines (design, electronics, mechanical) working in parallel, but relatively independently of each other. It is also commonly used with manufacturing processes being designed in parallel with the product, but with little feedback between processes. Concurrent engineering can be improved by having a multi-disciplinary team that truly involves all disciplines required for the project in every design and take it beyond the realms of the organisations, involving the suppliers and customers within the project boundaries. In this way, the team members work not in parallel, but as a single entity. Though this more "inclusive" form of concurrent engineering is not included in the scope of this paper, it is demonstrated in the case study.

The traditional Prototype as Design technique, as used by the NASA's Ames Research Center, is very useful in creating unique, one-of-a-kind research hardware for small, high-risk projects (Mulenburg, 2004). It is a useful technique in NPD projects as it often helps to produce better results faster. With the relatively recent advent of newer and faster RP technologies, both virtual and physical, a higher rate of design iteration can now be achieved, which often results in better project outcomes. The incorporation of these technologies into the design effort can be seen as a Rapid Prototype as Design process (RPaD) (Diegel et al, 2005).

1.1 *Prototype as Design*

Traditional project management tends to focus on the areas of Cost, Time, and Quality. With global commerce supported by technology and communication made possible by the internet, time is now 24/7 and technical challenges are addressed on a global basis using team members in different countries and time zones. In this changing world, Time is rapidly becoming the most critical factor to project success. High-tech products that come to market six months late but on budget earn 33% less profit over 5 years. In contrast, coming out on time and 50% over budget cuts profit by only 4% (McKinsey & Co, 1989).

Companies that develop products on budget, but in shorter times, develop commercial advantage and increased flexibility.

Prototype as Design (PaD) shows significant success in simplifying and speeding up the development of unique research hardware with large cost savings. PaD is a means of using the old artisan's technique of prototyping as a modern design tool. Prototyping is one of the oldest product development techniques in the world and has been used by artisans for centuries. These artisans created prototypes of their ideas, to ensure that they worked, before making the planned primary artefact. PaD is useful in producing one-of-a-kind projects by eliminating some of the formality of the traditional 'stage-gate' design processes. The front-end design stages of NPD projects, however, can also be seen as one-of-a-kind design challenges and are therefore very applicable to the PaD process.

It is often impossible to precisely specify requirements at the fuzzy front end of a project. Even if possible, it may be undesirable to do so (Frame, 2002). This often makes PaD critical to projects, as it is a highly interactive, integrated process that allows multiple iterations of complex aspects of a R&D product to be quickly evaluated and adapted into a properly functioning whole (Mulenburg, 2004). This 'whole' almost always meets the users' needs, as they actively participate in the design. It increases their buy-in with each improved iteration of the prototype.

The need for using this new/old process in NPD companies is largely due to the proliferation of highly functional and easy to use Computer Aided Design (CAD) tools to skilled and versatile engineers. One of the problems with CAD, however, is that it does not always reflect reality accurately. In a review of 72 development projects in the computer industry (Eisenhardt and Tabrizi, 1995) it was found that the common perception that CAD greatly enhanced product development time, was often not the reality. Further anecdotal experience also shows that the extensive use of CAD tools can result in both excessive time expended in design, and a lack of imbedded reality in the final product. A design may look good on the computer screen, but will it meet user needs and can it be made as designed? Often many design changes occur during the manufacture of these pretty designs that increase both schedule and cost to the project without a commensurate increase in product usability or quality. Beautiful 3-D computer models and detailed CAD drawings can result in difficult to manufacture hardware that requires expensive fabrication processes that add cost or increase schedule.

Prior to computers, designers who often were not engineers, converted engineering sketches into finished drawings for manufacture. While doing so, much design detail was added to not only meet manufacturing's needs, but also to ensure the end user's satisfaction. Computers have gradually eliminated the designer's role, leaving a gap that engineers are often not trained to fill: making the design manufacturable and optimizing its desired usefulness. One development in calibrating and optimising virtual product and process designs has, for example, addressed this gap in an automotive industry application, creating millions of dollars in savings in design lead time, product quality and performance (Singh, Vijayaraghavan 2001). For many high-tech products, design time can be saved and expensive rework eliminated during fabrication by using PaD.

Barkan & Insanti (Barkan and Insanti, 1992) advocate prototyping as a core development process for a way out of this dilemma. Mulenburg (2004) sees this is a major contributing factor in the 70~80% of projects that never make it through complete development, or fail in the marketplace because of compromises made during development that reduce content to save cost and schedule.

Mulenburg (2004) sees one of the major contributors to problems, during the traditional linear design process, as being an attempt to make every part as effective as possible. Trained in design, many engineers try to optimize every portion of a product to create an optimized whole, which is exactly the opposite of what is required for both speed and parsimony in design. The result is sub-optimization adding both time and cost to the design process without optimizing the final product.

The desired product must meet the needs of the intended user, and these needs must be agreed upon and defined as early and as clearly as possible. Reality is that things are often optimized simply because they can be; not because they need to be. When only a few units of a product will be built, for example, is anything achieved by a lengthy comparison of which fasteners to use in order to optimize the highest quality with the lowest cost when only a minimum order quantity will be purchased anyway? If the functional requirements can be adequately met by an early choice, it is much more important to make the selection and move on to more complex aspects of the design that may need extra time to ensure they meet the desired needs. In new product development, time truly is money.

1.2 ***Rapid Prototype as Design***

The advent of the latest RP, CAD, computer aided engineering (CAE) and computer aided manufacturing (CAM) technologies has added a new twist to the traditional PaD process. It is now transforming into a 'Rapid Prototype as Design' process. This new generation of tools allows engineers to perform complex finite element analysis (FEA) calculations on their products, to test for any thermal or structural problems, or to simulate how plastic may flow through an injection molding tool.

Physical prototypes play a great role in NPD as they are a means of demonstrating scale and realism in a way that paper drawings and computer 3D models can not. The translation from two dimensional to three dimensional representations is a key stage in NPD (Vervis, 1994). The progression of prototypes can be seen as going from two dimensional to three dimensional on-screen, to three dimensional physical models. Only a three dimensional physical model can effectively achieve the real suitability of a physical product (Broek et al, 2000). There are large differences in perception between a user seeing a CAD model and then seeing a real physical working model. The additional tactile, haptic and true three dimensional perception produces two completely different responses in the user (Emori, 1977).

The overall design process now looks somewhat as follows: Initial conceptual sketches are still often done in 2D, both on paper and on the computer. More advanced conceptual design and engineering design models are then 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 for injection molding. Both these methods were time consuming and expensive.

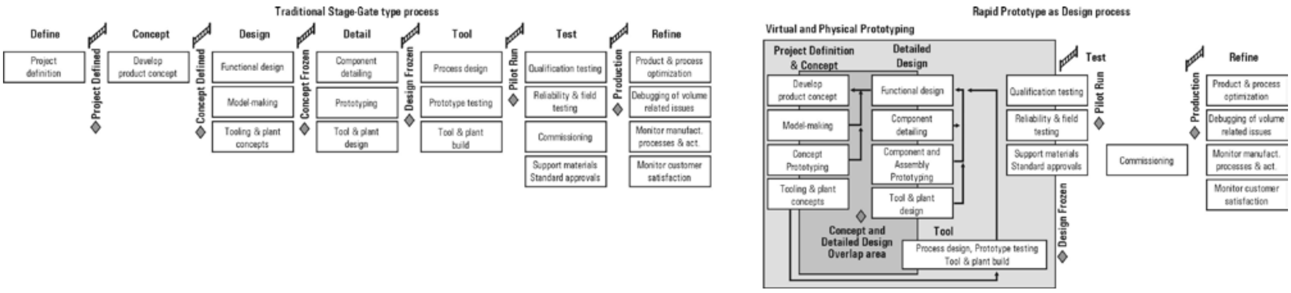

Figure 1: Comparison of Traditional and RPaD Processes

The latest RP technologies, such as stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM) and 3D printing now allow physical prototypes to be produced often within hours (Krar and Gill, 2003). Fused metal deposition systems and processes such as Laser Engineered Net Shaping (LENS) and Electron Beam Melting offer potential for rapid manufacture of end-use products and Functionally Graded Materials (FGM) in high temperature metals including titanium alloys (Hopkinson, Hague and Dickens, 2006).

The RP process begins by taking a 3D computer generated file and slicing it into thin slices (commonly ranging from 0.1mm to 0.25mm per slice depending on the technology used). The RP machine then builds the model one slice at a time, with each subsequent slice being built directly on the previous one. The technologies differ mainly in terms of the materials they use to build the part, and the process used for creating each slice of the model (Chua and Leong, 2003).

Some of the earlier RP processes, which were only able to make plastic-like parts, are now producing metal parts in aluminium, titanium, and even stainless steel (Wohlers, 2005). 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 not only simulating the behaviour and performance of electronic circuits, but also for rapid prototyping complex double-sided (and even multi-layer) through-hole plated circuit boards.

These technologies mean that it is now possible to construct highly advanced virtual prototypes, and then working physical prototypes 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 (Krar and Gill, 2003).

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 also 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.

Some of the tools that can effectively be used for software prototyping include visual development tools such as Visual Basic or C# which allow complex software systems to be prototyped relatively quickly as they remove much of the time needed to produce Graphical User Interfaces (GUI). Tools for programming embedded system devices and microprocessors have also immensely improved over the last few years, making it possible to program a working electronic system very quickly. The same goes for electronic design, in which an ever increasing arsenal of electronic design and simulation tools makes it easier to design working virtual and physical prototype electronic systems.

The prototyping tools used in the case study described here included a Dimension 3D Printer made by Stratasys to produce the plastic parts, rubber molding (from prototype parts), as a form of rapid tooling, to produce the polyurethane parts used in the blood pressure monitor cuff), Visual Basic 6 for the PC software, a preprogrammed chipset and electronic design from an existing product for the blood pressure monitor hardware, Altium Designer to lay out the circuit board and an LPKF Protomat S62 PCB prototyping system.

2 CASE STUDY

The Spengler SCVL Cardiovascular Lab is an innovative cardiovascular monitoring technology developed by a design team working concurrently in New Zealand, France and Taiwan.

Traditional blood pressure monitors measure only systolic and diastolic blood pressure. The SCVL Cardiovascular Lab is a USB-driven cardiovascular monitoring system that measures not only blood pressure, but also the Systolic Pressure Index (SPI) and Ankle Brachial Index (ABI) which show any arterial blockages, Pulse Pressure (PP), Mean Arterial Pressure (MAP), Cardiac Output (amount of blood pumped by the heart per minute) and Stroke Volume (amount of blood pumped by the heart per contraction). It gives a clear and comprehensive picture of a user's cardiovascular health, including the risk of coronary heart disease in the following ten years, based on the Framingham risk factor calculations.

The monitoring system includes batteryless sensing devices that simultaneously take measurement on both arms. The SCVL is driven by a PC and displays the real-time pulse waves on the screen of the computer and uses novel algorithms to compare pulse waves to one another to calculate SPI or ABI.

Figure 2: The Cardiovascular Lab software and hardware

Though Spengler already manufactures blood pressure monitors, they are of a 'conventional' type, so the SCVL represented a new platform product for them. All their current products were self-contained hardware devices, so this was also their first foray into a product that included PC based software with the blood pressure monitoring hardware, thus adding a level of complexity to the management of the project.

The project began with the identification of a need, by French doctors, for a relatively low cost system capable of measuring ABI as an indicator of peripheral arterial disease. The doctors approached Spengler, a French manufacturer of blood pressure monitoring equipment, about developing such a device. Spengler formed a cross disciplinary team including medical experts in France, mechanical design, ergonomics and user centered design (UCD) experts in New Zealand, electronics experts in Taiwan and manufacturing and software expertise in all three locations. After an initial three day face-to-face meeting by the entire design team in Taiwan, all subsequent communication took place using telephone, e-mail and the Skype internet phone/ video/ conferencing system as well as the exchange of data through a server located in Taiwan. At the first meeting, the specifications and requirements for a wrist version and upper arm version of the blood pressure monitor were agreed upon through doctor consultations and test user groups.

It was also identified that the electronics from one of Spengler's existing blood pressure monitor that already had on-board USB communication could be used with minor modifications and a re-laying out of the printed circuit board (PCB). Within 2 days, a working prototype, though not of the right shape or size, was produced by manufacturing a double sided PCB on an LPFK S62 PCB prototyping system, and was tested to ensure that it could transmit live data to a PC over USB.

This reuse of existing products and technologies forms an important part of prototyping, particularly at the early project stages, when one is often still only testing concepts and ideas, for which it would simply not be worth expending the resources to design complete new systems, which is likely to change as the concept gets refined during the later stages of the design process.

Within the three weeks that followed, the design team had daily video conferences with the entire team contributing to all aspects of the design. In particular the user requirements combined with the overall ergonomic requirements were investigated by the whole team from a hardware, software and electronic point of view. It should be noted that each team members' area of expertise was far from the only area they contributed to. The software engineer, for example, had much input in the design of the hardware, as the way the user interacted with the hardware affected the way in which they interacted with the software.

In this initial phase, seven separate iterations (four for the wrist model and three for the upper arm model) of housing mock-ups were designed, first in Solidworks as virtual prototypes, and then printed on a Stratasys Dimension 3D printer, and painted to look like finished products, so that they could be tested for ergonomics and ease of control with a group of test users. Though these initial mock-ups were not all working prototypes they still allowed much of the functionality to be tested from a user interaction and aesthetic point of view.

It was important to have the electronic and software engineers working closely with the designers and ergonomists during this stage so that any decisions made could be rationalized from a manufacturing point of view and by how a design decision made in one area impacted on those in other areas. A simplistic example of this is how an increase in the size of a PCB has obvious impact on the mechanical design of its enclosure.

That is not to say that the engineers constrained the creativity of the designers and stylists but rather that, by having the engineers personally involved in the design process, it helped to break down some of the barriers that can occur when each discipline works largely only on its own section of the project.

Throughout this stage, the software GUI was also being prototyped, in parallel with the hardware, in Visual Basic and was tested on the group of users for ease of use and access to features. Again, most of these early GUI prototypes had little real functionality behind them but were used to rapidly test user understanding and ease of use of the system. By the end of the first month of the project, the design team had formulated a concept that both met the user requirements, and also met all the constraints from a cost, mechanical, electronics, software and manufacturing point of view.

The detailed design and prototyping stage of the project now began with a complete mechanical, electronic and software design of the final concept. At this stage members of the manufacturing, marketing, and technical support team also became much more intimately involved with the project. The toolmakers, for example, to started planning out both the layout of the injection molding tools, and the time line to fit them into their production duties. The detailed design stage saw another 5 iterations of physical prototypes (three for the wrist model and two for the desktop model). The iterations consisted in refinements to the mechanical and electronic designs, particularly from a design for assembly (DFA) and manufacturing (DFM) point of view. The main moldings for the plastic assembly, for example, were designed so that the molds could be machined rather than spark eroded with electrodes to save on the time to get the product into production.

The software too went through several iterations, both to ensure that stability of the two-way communication with the blood pressure monitors, and to ensure that it was as intuitively easy to use as possible. This period also saw the working prototypes extensively used in usability testing with doctor and patient groups, which allowed further refinements, both to the hardware, and to the software usability.

The final fully working prototype for the SCVL Cardiovascular Lab, including the complete software package, two wrist version blood pressure monitors and two upper arm version monitors was complete within just over two months of the project start. The following three months saw the factory getting the product ready for production, most of which time was involved with tooling up for the injection molded components, setting up of assembly and test procedures and clinical validations of the product through the use of the working prototypes. This period also saw further refinements and debugging to the electronic and software components of the product to make them as reliable as possible. The final prototypes were also used to prepare marketing material so that, as soon as the product was ready for production, the marketing campaign could begin without delay.

By the end of the fifth month, the first off-tool samples were ready, and final product testing was undertaken. The high use of prototypes meant that the first off-tool samples were extremely close to the final production models, and only very minor modifications to the tool (mainly with fine-tuning the snap-fits of some of the components) were then required for the first pre-production run.

3 CONCLUSION

As newer virtual and physical RP technologies emerge, the way in which we use them to more effectively manage the NPD process must evolve in tandem. Indeed, the traditional NPD processes must evolve into Rapid New Product Development management processes.

The combination of RP 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.

The deployment of concurrent engineering in a more inclusive manner, in which team members from different disciplines actively contribute to areas of design other than their own, can also be used to increase the quality of the project outputs.

The case study of the Spengler SCVL Cardiovascular Lab briefly described in this paper is an example how the combined use of available virtual and RP technologies can shorten the product development cycle even for products that represent new platforms to a company.

The project utilized a non-collocated collaborative design team in which all team members, regardless of their particular discipline, were involved in all aspects of the product. The continuous use of physical prototypes throughout the development process allowed many areas of complexity to be identified as well as allowing the interactions between the mechanical, electronic and software aspects of the product to be identified and improved.

The many physical prototypes, from non-working to fully working were also useful in assessing the product through the eyes of the various user groups.

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