

A Case Study of Rapid Prototype as Design in Educational Engineering Projects*

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Many engineering courses are characterized by having to produce one-off, technically complex artifacts to demonstrate that learning has been achieved. This paper introduces 'Rapid Prototype as Design' as an effective methodology to help students produce effective results in their engineering projects. This paper presents a case study on the GlucoFridge, a pocket-sized, battery powered, insulin refrigerator which was a technologically complex project involving a variety of technologies. The product was developed in three months through the tight integrated use of virtual and physical rapid prototyping technologies that allowed for an extremely fast reiterative design approach and a short development time.

INTRODUCTION

MANY ENGINEERING COURSES expect students, as part of the course, to produce physical artifacts that demonstrate their ability to apply the knowledge that they have learned in a quasi-real-world situation. These projects often involve the development of a one-of-a-kind piece of equipment or machinery and often involve the use of multiple areas of technology, such as electronics, mechatronics, mechanical engineering, software, manufacturing and so on. They are, of course, also characterized by having to produce results within a relatively tight time-frame, as dictated by the length of the course.

The traditional Prototype as Design technique, as used by the National Aeronautics and Space Administration's Ames Research Center, proves very useful in creating unique, one-of-a-kind research hardware for small, high-risk projects [1]. It is therefore a useful technique to teach engineering students as it often helps them to produce better results faster.

With the relatively recent advent of newer and faster rapid prototyping technologies, both virtual and physical, students can now achieve a much higher rate of design iteration, which often results in a better project outcome. The incorporation of these technologies into the design process can be seen as a Rapid-prototype as Design process.

PROTOTYPE AS DESIGN

When managing the design of unique and complex engineering projects, one must ask the

question as to whether traditional project management is up to the task. According to Frame [2], '... traditional project management is broken.' as it has failed to adapt to meet changing times and technologies. Whitney [3] notes that: 'In many large companies, design has become a bureaucratic tangle, a process confounded by fragmentation, overspecialization, power struggles, and delays.'

Traditional project management tends to focus on what is often called the 'holy-triangle' of project management: cost, time and quality (which are usually defined by the technical requirements of a project). With global commerce supported by technology and communication made possible by the Internet, time is now 24/7 and cost and technical challenges are addressed on a global basis using team members in different countries, with different cultures and time zones, languages, and methods. In this changing world, New Product Development time is rapidly becoming the most critical factor to project success. High-tech products that come to market six months late but on budget will earn 33% less profit over 5 years. In contrast, coming out on time and 50% over budget cuts profit by only 4% [4]. If companies develop products on budget, but in shorter times, they develop a commercial advantage and increased flexibility.

Design by Prototype is a technique in use by such organizations as the National Aeronautics and Space Administration's Ames Research Center [5]. It shows significant success in simplifying and speeding up the development of unique research hardware with large cost savings. Design by Prototype is a means of using the old artisan's technique of prototyping as a modern design tool. Prototyping is probably the oldest product development technique in the world and has been used

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by artisans for centuries. These artisans created prototypes of their ideas, to ensure that they worked, before making the primary artifact they were planning. Traditional Design by Prototype is useful in creating hardware for one-of-a-kind projects by eliminating much of the formal engineering design process.

It is often impossible to precisely specify requirements at the fuzzy front end of a project. Even when possible, it may be undesirable to do so [2]. This often makes Design by Prototype critical to projects. Design by Prototype is a highly interactive, integrated process that allows multiple iterations of complex aspects of a desired R&D product to be quickly evaluated and adapted into a properly functioning whole [1]. This 'whole' almost always meets the users' needs, as they actively participate in the design as it evolves during development. It gets their buy-in with each further improved iteration of the prototype.

The need for using this new/old process in new product development companies is largely due to the proliferation of highly functional and easy to use computer-aided design (CAD) design tools to highly skilled and versatile engineers. One of the problems with CAD is that it does not always reflect reality accurately. In a review of 72 development projects in the computer industry [6] it was found that the common perception that Computer Aided Design greatly enhanced product development time, was often not the reality. Further anecdotal experience also shows that the extensive use of computer design tools can result in both excessive time expended in design, and a lack of imbedded reality in the final product. A design may look pretty on the computer screen, but will it meet the users' needs and can it be efficiently 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 three-dimensional computer models and detailed CAD drawings can result in difficult to manufacture hardware that requires expensive fabrication processes that add cost and/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. For many high technology products, much design time can be saved and expensive rework eliminated during fabrication by using design as prototype.

Barkan and Insanti [7] advocate prototyping as a core development process for a way out of this dilemma. Mulenburg [1] 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 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 [1]. Trained in design, many engineers try to optimize every portion of a product in trying 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. An old Zen proverb captures this problem in a few effective words: Perfection comes not when there is nothing more to add, but when there is nothing more to subtract.

The desired product must, of course, meet the basic needs of the intended user, and these needs must be agreed upon and defined as clearly and as early into the project as possible. Reality is that things are often optimized simply because they can be; not because they need to be. As an example, when only a few units of a product will be built, 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.

RAPID PROTOTYPE AS DESIGN

The recent advent of the latest rapid prototyping, computer aided design (CAD), computer aided engineering (CAE) and computer aided manufacturing (CAM) technologies has added a new twist to the traditional prototype as design process. It is now transforming from a 'prototype as design' process into a 'Rapid Prototype as Design' process.

This new generation of tools now allows engineers to, for example, relatively easily perform complex finite element analysis (FEA) calculations on their products, to test for any thermal or structural problems, and even to simulate how plastic may flow through an injection molding tool during manufacturing.

Physical prototypes play a great role in product development as they are a means of demonstrating scale and realism in a way that paper drawings, and even computer 3D models, cannot. The translation from two-dimensional to three-dimensional representations is a key stage in product development [10]. 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 [11]. There are invariably large differences in perception between a user seeing a traditional CAD model only and then seeing a real physical working model. The additional tactile, haptic and true three-dimensional perception produce two completely different responses in the user [12].

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 CNC (computer numerically controlled) machining or to produce expensive tooling into which the part could be injection molded. Both these methods were both time consuming and expensive.

The latest generation of rapid prototyping technologies, such as stereolithography (SLA), selective laser sintering (SLS) and fused deposition modeling (FDM) now allow physical prototypes to be produced within hours rather than days [13].

The rapid prototyping process begins by taking a 3D computer generated file and slicing it up into thin slices (generally ranging from 0.1 mm to 0.25 mm per slice depending on the technology and machine 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. 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 [14]:

- SLA uses a photosensitive epoxy resin cured by a UV laser. The laser traces each slice of the model in a scanning pattern, which cures the resin down to the desired slice thickness as it passes over it. As each slice is finished, the build platform is dropped one step into the vat of resin and another layer of resin is applied on top of the previous one so it can be traced for the next slice. This continues until the model is complete after which it is removed, cleaned up, and fully cured in a UV oven as a secondary operation.
- SLS uses a similar process but uses a nylon based powder as a build material (though many other materials are now also available) and melts (sinters) it with a laser. In this case, a thin layer of powder is spread onto the build platform, and the laser traces the slice, bonding the plastic powder together. The slice is then

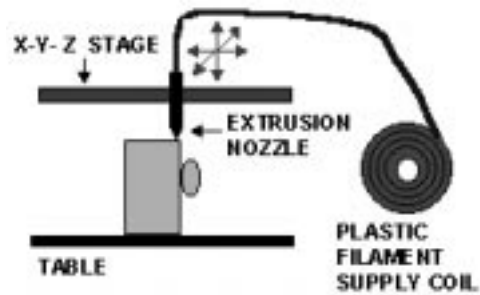


Fig. 1. The FDM process used by the Dimension printer.

lowered one step and another layer of powder is spread for the next slice. Each slice bonds to the previous slice.

- FDM works by extruding a thin ribbon of plastic as the nozzle of the machine traces each slice. It is, in effect, not dissimilar to an inkjet printer but prints in plastic instead of ink.

There are many other technologies that use slightly different materials and process to the above. Most, however, work on the principle of building the model one slice at a time.

The rapid prototyping system used in the case study described in this paper was a Dimension BST 3D Printer, manufactured by Stratasys. The Dimension printer costs US\$24,000 which is a relatively low cost in comparison to the more expensive SLA and SLS systems available. This system uses a FDM-based system that extrudes a thin ribbon of ABS plastic to trace each slice. It allows for a slice thickness of 0.25 mm per layer.

The parts produced are strong plastic components that are well suited to functional testing and can easily be painted to reproduce the aesthetics of the production product.

The software included with the Dimension printer takes care of the model slicing automatically. All the user has to do is decide on the orientation in which the model is to be built, either to maximize strength, or to give it the best surface finish.

Some of the above rapid prototyping processes, which were previously only able to make plastic-like parts, are now becoming able to produce metal parts [15]. 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 behavior and performance of electronic circuits, but also for rapid prototyping 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 more iterations of a design within a shorter timeframe. This, in turn, potentially allows for products that are even better suited to their intended users in even shorter times [13].

CASE STUDY—THE GLUCOFRIDGE

The following case study, undertaken by product development students at Massey University, in Auckland, New Zealand, demonstrates how using these virtual and physical rapid prototyping technologies can help in bringing a new product to market faster.

The problem statement

The latest WHO estimate for the number of people with diabetes, worldwide, in 2000 is 177 million. This will increase to at least 300 million by 2025. It has long been known that the number of deaths related to diabetes is considerably underestimated. A plausible figure is likely to be around 4 million deaths per year related to the presence of the disorder. Overall, direct health care costs of diabetes range from 2.5% to 15% annual health care budgets, depending on local diabetes prevalence and the sophistication of the treatment available [8].

When traveling, diabetics currently have to keep their insulin cool by putting it in a hotel refrigerator (if there is one available) and by carrying cooling devices such as icepacks when they travel away from their hotel. Insulin should be kept at temperatures below 25°C. Many countries have temperatures ranging from 20°C to 40°C, which rapidly spoils insulin. The American Diabetes Association recommends that insulin be stored in a refrigerator [9]. Many hotels also do not have room refrigerators. These factors make it troublesome for diabetics to travel as they have a constant worry about whether their insulin is safe.

There are currently 3 commonly available cooling methods for insulin dependant patients as well as a number of derivative solutions. They are as following:

1. **Ice packs:** This still seems to be the most commonly used means of refrigeration. Ice packs are frozen and put in a cooler box in which the insulin is transported over short trips. **Cons:** This is very bad for the insulin as it often comes in direct contact with the ice. Freezing may cause crystallization, resulting in variable potency. Chilled insulin vials should be inspected for crystals and particulates before use.
2. **MEDIce ice packs:** These are refreezable ice packs filled with a nontoxic gel that last 30% longer than ice cubes. Travel Organizers with MEDIce have a compartment in which the MEDIce Ice Packs are inserted so that there is no direct contact with the insulin. **Cons:** Must be frozen for 46 hours before use. Does not last more than a few hours. Gel packs often leak with change of atmospheric pressure.
3. **FRIO Wallets:** This device came on the market in 1999 and it is designed to keep insulin cool and safe for 48 hours. The main advantages are

that there are no bulky ice packs, you do not have to worry about finding a freezer to get supplies of ice and the wallet is light to carry. It is activated by immersing it in cold water for 15 minutes. The panels of the wallet contain crystals and these expand into gel with the immersion in water. The wallet remains at a cool temperature for 48 hours, according to the prevailing conditions. The system relies on the evaporation process for cooling. **Cons:** The inner bag stays very damp despite drying it with a towel as recommended and so the labels on the insulin vials start to disintegrate. Even though the unit is damp, the instructions say that the cooler pouch should not be put in a plastic bag because it does not work so well. This makes it inconvenient to keep with other items that may be damaged by the dampness.

The GlucoFridge portable insulin refrigerator

The GlucoFridge is a portable, battery powered, pocket sized refrigerator. This 'worlds smallest' refrigerator is designed for carrying insulin (or other medication), which needs to be kept at a constant and cool temperature. The applications for this technology are numerous, from transporting insulin, blood and sperm samples to anti-venom vaccines. It consists of a refrigeration unit that has drawers made for different size injection devices or medical samples. The unit comes equipped as standard with drawers for the most popular insulin injection devices.

The refrigerator is powered by rechargeable Lithium ion batteries and is of a size that allows it to fit in a jacket pocket. As its cooling technology it uses a Peltier device (heat pump). The novelty of this product lies in its portability, its uniquely small and compact size, and in its application of Peltier device technology. There is currently no other such product available.

The GlucoFridge is designed to be plugged into mains power at night, thus cooling the insulin and simultaneously charging the battery. Away from the hotel, it is powered by the batteries. As batteries, it uses two lithium ion rechargeable batteries giving it a life 12 to 24 hours depending on how many times it is opened during the day.

Although many people enjoy traveling, patients with diabetes often fear or avoid travel. This product gives diabetics both freedom of mind and freedom of movement when traveling.



Fig. 2. GlucoFridge final pre-production prototype.

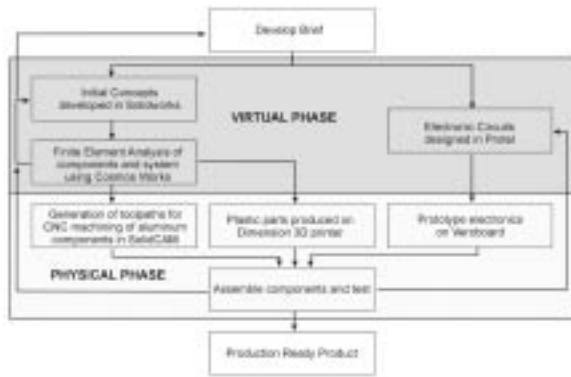


Fig. 3. GlucoFridge design process.

The GlucoFridge design process

The GlucoFridge went through three major, and several minor, design reiterations, the first two of which identified the major technical problems to overcome, before arriving at the final production design.

The design process began with the inventor identifying the need for the product, and researching the market to the extent that a medical device manufacturing company was willing to take on the project, both from a manufacturing and distribution point of view, upon receiving a working prototype. From here, the following design process was used.

The first two weeks of the project were spent producing a conceptual CAD design of how the product might work from an engineering perspective. The software used for this was Solidworks, which has a relatively short learning curve and quickly allows students to produce complex engineering models to simulate both the aesthetics and engineering functions of their projects. The students designed initial concepts within a time span of 4 to 5 days, which were then perfected and detailed over the following week as problems with the designs were identified by the students and lecturers.

At the same time, a large range of Peltier devices (thermoelectric coolers) was ordered so that a series of tests could be undertaken to test the ideas that were to be at the core of the product. Peltier devices are semiconductor devices that, when current is passed through them, get hot on one side and cold on the other. These devices are commonly used on small camping refrigerators, for example.

Though it may not always be considered a true use of technology, the Internet should not be ignored as a tool to speed up the product development process. It is a rich source of technical information and an extremely effective way of rapidly sourcing components. Most electronic components, for example, can often be sourced within a few days, and the extra cost this may involve is usually insignificant when compared to the benefits of the time saved. During the first 2 weeks of the project, the Internet was used

extensively, both to order a wide range of Peltier devices from several manufacturers, and to obtain much information about thermoelectric cooler theory.

From the initial CAD design, a thermal finite element analysis (FEA) was performed to calculate the size of the cold plate that would be required to keep two vials and the insulin compartment of two NovoPen III (a commonly used insulin injection device) at a temperature of approximately 10°C. The initial calculations were first done on paper to select the most likely Peltier candidates, and these selections were then run through a computer simulation. The FEA was done using the CosmosWorks add-in to Solidworks, which allows both stress and temperature analysis of systems. CosmosWorks is setup such that students can very easily use the stress and deformation analysis sections of the software. The thermal analysis section of the software did however require them to receive extra tutoring in thermodynamics in order to better understand all the variables the software was asking them for. In addition, FlowWorks was also used to simulate how the air was likely to flow through the system and allowed the creation of extra turbulence around the heat-sink area to help cool the system.

The initial design was based on using a Sony Handycam style 7.6 V, 3800 mAh rechargeable battery running a 7.8 V, 5.5 W Peltier device sandwiched between a large hot plate heat-sink and a cylindrical cold plate extrusion.

From within the CAD software, tool-paths for all the aluminium components were generated within a very short time, and the aluminium components were then rapidly produced on a CNC milling center. This effectively demonstrated the tight integration now available between CAD and CAM systems. The CAM system used for this particular project was SolidCAM which is a system that is tightly integrated into Solidworks. Though, at its simplest, SolidCAM can almost completely



Fig. 4. First iteration of GlucoFridge design.

automatically generate the toolpaths for complex machining operations, the students soon found that the toolpaths generated were inefficient and substantially increased machining time. They therefore repeated the exercise of creating the toolpaths by first breaking the components down into more basic machining operations and created separate routines for each operation. The heat-sink designs used in the initial GlucoFridge design were relatively simple, and the time to go from the finished CAD model to the CNC mill cutting metal was approximately one hour.

A rapid prototype of all the plastic components was printed on a Dimension 3D printer which produced ABS plastic parts of the design which was assembled and tested. The time taken for the first set of parts was 54 hours.

A simple version of the temperature control circuit was prototyped on Vero-board to allow for testing, while at the same time the more complex real temperature control circuit was still being designed.

The initial tests revealed an almost immediate problem in reaching the target temperature. Though it had initially been hoped that it would be possible to reach the target temperature without the use of a fan, it was almost immediately found that, even with a large and efficient heat-sink for the hot side of the Peltier device, the system was not quite efficient enough to dissipate enough heat for the temperature differential created by the Peltier to allow the desired refrigerator temperature to be reached.

The design was immediately modified to allow for the use of a 40 mm × 40 mm × 6 mm fan, and a new plastic top cover component was printed and the unit was once again tested.

In this second batch of tests on this minor revision of the first design, the cold plate easily reached the desired temperature, but a second major problem soon became apparent: The design included an electronic temperature control circuit which, when the cold plate reached the lower end of the target temperature range of 5°C, would cause the power to the Peltier to be switched off. When the temperature, after gradually increasing, then reached the upper end of the temperature range of 15°C, the Peltier would switch back on. The intention of this feature was to extend the battery life by making it do as little work as possible.

What became almost immediately apparent was that, once the power to the Peltier was switched off, it only took minutes for the cold plate to climb back up to the upper end of the temperature range. Even with the polystyrene insulation that was used to insulate the system from the outside ambient temperature, the temperature still climbed too rapidly, which meant that the battery had to switch on more often in order to keep the temperature in the desired range. This meant that the refrigerator only had a battery life of approximately six hours, which was much less than the minimum requirement of 12 hours of battery life.

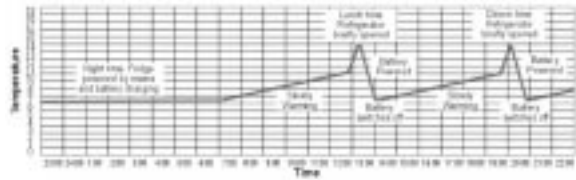


Fig. 5. Desired effect of temperature control circuit.

A solution was soon found to this problem: To build the entire cooling assembly into the inside of a vacuum flask type cooling container. The vacuum would act as an effective insulation that would ensure that, once the cold plate reached the low end of the temperature range, the Peltier would switch off, and the cold plate would then, because of the effective insulation, take a long time to warm back to the upper end of the temperature range.

This major change forced a complete redesign, as the vacuum flask meant that the battery could no longer be on the rear of the unit. This, in turn, meant that the size and shape of the Handycam type battery made it less than ideal for the product, so a new battery needed to be found. Some Internet research and fast tests were carried out with a variety of batteries, and it was found that four 2500 mAh, 1.2 V AA size batteries, in combination with a 3.75 V, 5.5 W Peltier device could achieve the desired temperature levels. This appeared to be an ideal solution as the AA batteries were substantially smaller and would allow for a smaller product.

New CAD models were generated to see if the AA batteries could be configured in such a way as

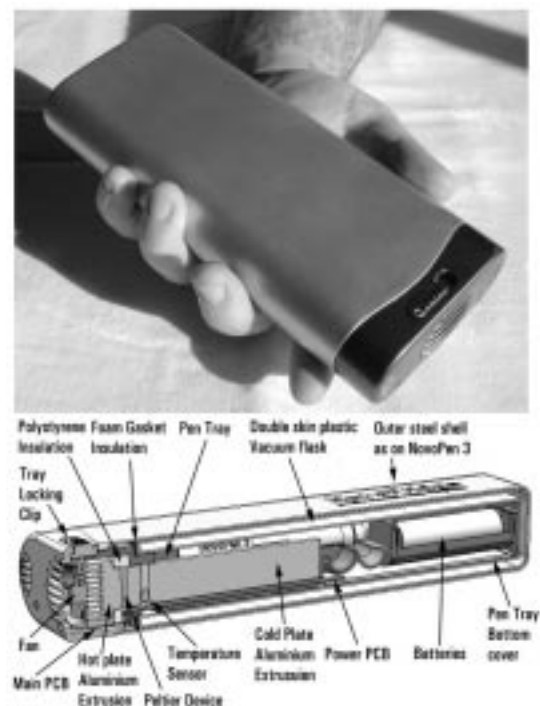


Fig. 6. Second design iteration of GlucoFridge.

to fit within the vacuum flask together with the insulin vials and pens. This proved possible by completely changing the configuration of the hot plate, Peltier, and cold plate, and by changing to a pair of 25 mm fans. Another prototype was made of the plastic and aluminium components. The lead-time to get a sample of the vacuum flask made was about 3 weeks, so tests were initially carried out with an off-the-shelf vacuum flask of the same volume as that in the design.

This second prototype proved to work, and was taken to potential users for comment. From these focus groups a few minor problems and a potentially major problem were identified.

One of the minor problems was one of battery status and temperature status indication, which was easily solved through the use of multiple coloured LED indicators. Other minor problems identified included the need for the addition of a physical on/off switch so that the unit could be physically switched off when not in use, and the effectiveness of the locking clip that locked the medication tray into the vacuum container and provided a tight seal between the two.

The potentially major problem was to do with the batteries. Almost all the users immediately asked about the possibility of putting in regular, non-chargeable AA batteries. Though this was, in theory possible, the batteries had to be good quality, high mAh-rated batteries capable of providing a high continuous current output (such as the Energizer Titanium e2 batteries, for example). This was perceived as a major problem by the users because of the perceived high chance of them using the product with unsuitable AA batteries. If the wrong type of batteries were used, they would not only tend to get very warm, thus canceling the effect of the cooling, but also run the risk of being damaged and leaking inside the product. It was therefore indicated by the users that it would be better if the batteries were not changeable by the user, and they even indicated a preference not to use standard AA batteries in order to eliminate the risk of the wrong type being used. The potential for condensation forming around the battery compartment was also identified as a worry by the users. It was therefore decided that it would be preferable to have the batteries outside of the vacuum flask.

From this user feedback, the third major design iteration was entered into, and a new type of battery was selected. The new batteries were to be two 3.7 V, 2200 mAh lithium ion batteries in parallel. These batteries, at 18.3 mm diameter and 65.2 mm in length, would not be easy to fit inside the vacuum flask unless it was made too big to fit in a pocket. The new design iteration therefore changed to a removable battery pack on the outside of the vacuum flask, which at the same time alleviated any risk of any heat produced by the batteries affecting the temperature of the insulin or creating condensation. The larger batteries also meant a small increase in the height

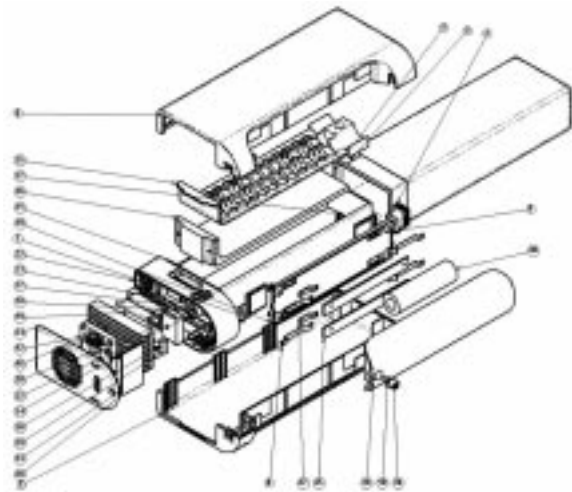


Fig. 7. Final GlucoFridge components.

of the product to allow for the batteries, but this in turn allowed for the use of a larger, and more effective, 35 mm fan which in turn made the system more efficient.

From this final rapid prototype, a few minor changes were made, such as moving the power adaptor connector to the back of the unit in order to make assembly easier, and the addition of extra air-vents to the front of the medication tray in order to make the warm air exhaust off the hot plate more effective.

At this stage, less than three months after the start of the project, it was deemed that the product was at a level where it would both meet customer expectations and be manufacturable at a cost acceptable to the manufacturing company.



Fig. 8. Final design iteration of GlucoFridge.

Table 1. Final design iteration: comparison of time and costs between rapid and traditional methods

Item #	Component	Process used	Design time	Make Time	Cost	Traditional process	Design time	Make time	Cost		
5,6	Body Plastic moldings	FDM rapid prototype	< 2 weeks	65 hours	\$750	Machine from plastic block	1 week	1 week	\$1000		
38, 39	Battery pack components	FDM rapid prototype				Machine from plastic block	1 week	1 week	\$1000		
22	Pen tray body	FDM rapid prototype				Machine from plastic block	1 Week	1 week	\$1000		
24	Pen tray cover	FDM rapid prototype				Machine from plastic block	1 Week	1 week	\$1000		
25	Pen tray inner plate	FDM rapid prototype				Machine from plastic block	1 Week	1 week	\$1000		
23, 29	Buttons	FDM rapid prototype				Machine from plastic block	1 week	1 week	\$500		
3, 4	Vacuum flask	Welded stainless				3 week	\$500	Welded stainless	2 days	3 week	\$500
26	Cold plate	Machined aluminium				2 hrs	\$100	Machined aluminium	1 week	8 hrs	\$400
16	Hot plate	Machined aluminium				2 hrs	\$100	Machined aluminium	1 week	8 hrs	\$400
7, 8, 37	Springs and contacts	Handmade or catalogue				5 hrs	\$200	Handmade or catalogue	1 week	5 hrs	\$200
	Total		< 4 weeks		\$1650		12-14 weeks	\$7000			

The entire project, including all CAD files and data, as well as the physical working prototypes was then handed over to the medical product company for manufacturing and production.

Discussion on the design process

The hands-on experience with Rapid Prototype as Design as presented in the GlucoFridge project was of great benefit to the students in applying a design management technique on a real project. It allowed them to not only experience the possibility of going through several iterations of a design, but also to see the incremental changes that each iteration brought to the performance of the end product.

Another side benefit of working with a Rapid Prototype as Design process was that it brought to the students a realization that, although most management and design methodologies and process are taught in a relatively linear manner, they must, in reality, often be applied in a much more parallel fashion. The process of prototyping any ideas as they come along means that you often have to look at parts of the manufacturing, and even marketing processes, even when you are still at the fuzzy front-end concept development stage. This clearly demonstrated how closely Rapid Prototype as design was related to concurrent engineering processes.

The components used in the final design iteration of the GlucoFridge are summarized in Table 1 in an attempt to show the time differences gained by using rapid prototyping, both virtual and physical in comparison to more traditional processes such as 2D drawing and manual machining.

Some things to note about the above table are that all rapid prototypes were made in a single build that lasted 65 hours and used \$750 of material. The machining costs represent the time and material costs as estimated by experienced University workshop staff, and do not therefore represent commercial rates. The Design times

include all testing of components, including stress and thermal testing. The design times estimated in the traditional processes column are based on 2D drafting of the designs and physical testing of the components. These could only be roughly estimated by workshop staff based on their past experience with components of similar complexity and sizes.

The total times can also not be arrived at by adding all the individual times in series as many of the tasks are, in fact, done in parallel. The long lead time for the stainless steel vacuum flask, for example, was alleviated by sending it to the sub-contractor as soon as it was finalized in the design, and it was therefore given obvious priority in the design process. The total time for the traditional processes methods was therefore arrived at through estimates from experienced workshop staff.

CONCLUSIONS

Engineering students are often expected, as part of their course, to produce physical artifacts that demonstrate their ability to apply the knowledge that they have learned. These projects often involve the development of a one-of-a-kind piece of equipment or machinery and often involve the use of multiple areas of technology, such as electronics, mechanical engineering, software, manufacturing and even marketing. They are, of course, also characterized by having to produce results within a relatively tight time frame, as dictated by the length of the course.

Rapid Prototype as Design can be seen as a natural evolution of the more traditional Prototype as Design process facilitated by the advent of improved CAD, CAE and CAM technologies as well as the proliferation of low-cost rapid prototyping technologies.

The ability to effectively integrate these many existing and emerging technologies into the new product development process has the potential of giving engineers the ability to produce new high technology products at an increasing rate.

The GlucoFridge case study described in this paper employed a rapid prototype as design process and successfully completed three major design iterations, each to working prototype level within a time span of less than three months.

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