AC 2012-3698: PROTOTYPING STRATEGIES: LITERATURE REVIEW AND IDENTIFICATION OF CRITICAL VARIABLES

Mr. Edward James Christie
Dr. Daniel D. Jensen, U.S. Air Force Academy

Dan Jensen is a professor of engineering mechanics at the U.S. Air Force Academy where he has been since 1997. He received his B.S. (mechanical engineering), M.S. (applied mechanics), and Ph.D. (aerospace engineering science) from the University of Colorado, Boulder. He has worked for Texas Instruments, Lockheed Martin, NASA, University of the Pacific, Lawrence Berkeley National Lab, and MSC Software Corp. His research includes design of micro air vehicles, development of innovative design methodologies, and enhancement of engineering education. Jensen has authored approximately 100 papers and has been awarded more $2.5 million of research grants.

Dr. Richard T. Buckley Ph.D., U.S. Air Force Academy
Devin A. Menefee, U.S. Air Force Academy

Devin A. Menefee is Cadet First Class at the U.S. Air Force Academy, and a mechanical engineering major.

Kyle Kenneth Ziegler
Prof. Kristin L. Wood, University of Texas, Austin

Kristin L. Wood is currently a professor, Head of Pillar, and Co-director of the International Design Center (IDC) at Singapore University of Technology and Design (SUTD). Wood completed his M.S. and Ph.D. degrees in mechanical engineering (Division of Engineering and Applied Science) at the California Institute of Technology, where he was an AT&T Bell Laboratories Ph.D. Scholar. Wood joined the faculty at the University of Texas in Sept. 1989 and established a computational and experimental laboratory for research in engineering design and manufacturing. He was a National Science Foundation Young Investigator, the Cullen Trust for Higher Education Endowed Professor in Engineering, and University Distinguished Teaching Professor at the University of Texas, Austin.

Dr. Richard H. Crawford, University of Texas, Austin

Richard H. Crawford is a professor of mechanical engineering at the University of Texas, Austin, and is the Temple Foundation Endowed Faculty Fellow No. 3. He received his B.S.M.E. from Louisiana State University in 1982 and his M.S.M.E. in 1985 and Ph.D. in 1989, both from Purdue University. He joined the faculty of UT in Jan. 1990 and teaches mechanical engineering design and geometry modeling for design. Crawford's research interests span topics in computer-aided mechanical design and design theory and methodology, including research in computer representations to support conceptual design, design for manufacture and assembly, and design retrieval; developing computational representations and tools to support exploration of very complex engineering design spaces; research in solid freeform fabrication, including geometric processing, control, design tools, manufacturing applications; and design and development of energy harvesting systems. Crawford is co-founder of the DTEACh program, a Design Technology program for K-12, and is active on the faculty of the UTeachEngineering program that seeks to educate teachers of high school engineering.

Prototyping Strategies: Literature Review and Identification of Critical Variables

Abstract:

Prototyping is an initial instantiation of a concept as part of the product development process. Prototypes serve numerous purposes both from a business and an engineering standpoint. Businesses use prototypes to gather detailed customer feedback on issues like aesthetics, ergonomics, and theme, as well as for marketing research and cost analysis. Prototyping is used by engineers to provide manufacturing and assembly data, to investigate system integration issues and to develop analysis and testing strategies. In some cases, prototyping is also used in the concept generation phase of the design process to assist designers to either expand or contract the set of possible concepts. Clearly prototyping is an important part of most design processes.

We define the ***prototyping strategy*** as the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s). Prototyping strategies include a variety of different options. In the broadest sense, prototypes can be either physical or virtual. Virtual prototypes can include computer simulations and/or engineering analysis. Physical prototypes can be developed either for a subsystem or for the entire system. In addition, physical prototypes can be either full size or dimensionally scaled and can be either fully functional or be created to exhibit only partial functionality. Additional choices that are part of a prototyping strategy include whether one chooses to develop prototypes for a number of concepts in parallel and whether one plans to develop a sequence of prototypes of a concept. The choices made for the prototyping variables identified above can make tremendous differences in the time frame, cost and effectiveness of the prototyping work. However, very little research has been accomplished to identify how these variables should be chosen for a specific design project.

In this paper we document an extensive literature review in the general area of prototyping. Prototyping strategies currently in use by a variety of different product developers are identified. When it is possible to identify either a business or engineering perspective, that perspective is noted. The wide variety of different prototyping strategies currently in use are identified and grouped into categories with similar characteristics. Specific differences in the prototyping strategies for business vs. engineering focused work are noted. Based on the literature review, the current state of the art for prototyping strategies is established. Of particular note is the fact that there is a dearth of information in the literature of how the decisions that determine a prototyping strategy are made. In light of this fact, an additional contribution of this paper is to hypothesize a set of characteristics of a design problem that can be used to optimize prototyping strategies.

Introduction

Prototyping has long been recognized as an important part of the product development process. In the top 20 companies currently identified globally as major innovators, R&D spending as a percent of sales ranged between 3.6% and 21.1%, with an average of 11.2%[1]. Total R&D spending in just these 20 companies totaled to $141.8 billion dollars. And yet, there are estimates that 40-46% of product development resources are spent on products that are cancelled or do not yield adequate returns[2]. This data is supported by a continuing PDMA study which has found that product success rates constantly hover just below 60%[3].

Prototype development often represents a large sunk cost that is marginalized by establishing a successful product line; it is thus necessary that prototyping efforts be efficient and have a high rate of success, in regards to the creation of an end product. While much work has been done on the "business" side of product development to increase success rates, little work has been done on the "engineering" side towards creating strategies which ensure success. The authors feel compelled to split the existing body of work on prototyping into "business" and "engineering" because there are two distinct viewpoints concerning prototyping that get lumped together, and thus unfortunately hide some of the current flaws.

What we term as the "business" side looks not at the physical creation of a product itself, but all of the logistics surrounding that creation. Their primary concerns are things like lead times, budgets, project efficiency, etc. Because these concepts are not unique to prototyping, there already exists a large body of similar work to draw from and tweak to fit product development projects. While these works are portrayed as "prototyping strategies", they really should be viewed more as "management strategies for prototyping projects." It is this confusion that may lead some to believe that there is a body of existing work on prototyping strategies.

What we term as the "engineering" side focuses on the actual product creation, with specific attention on the tools and processes that exist to help move from concept to reality. However, here we find very little solid strategy documentation. This may derive from the concern that the actual product development efforts are far too diverse to be able to apply any common strategies. At face value, building a better treadle pump has little in common with designing a new watch or developing industrial robots for use in automotive assembly lines.

We also look at how the "engineering" side lacks documentation towards taking into account "business" side concerns. While it may seem odd to suggest that engineers should also be acutely aware of these concerns, it is simply the nature of the organizational structure of business. As information moves "up the chain", it needs to be simplified and clearly expressed in order to be processed well. "Up the chain" will usually imply going from some form of engineering to some form of business consideration. An engineer that cannot clearly and concisely explain the impact of various decisions on a project's resource pool can quickly put a project in jeopardy.

In our opinion, it is this lack of strategy that is a large part of cause of prototyping breakdowns, which can leave projects overdue, over budget, and even ultimately fail to produce a successful product. However, we believe that there are overarching factors in prototyping that can be applied across all development endeavors, and that by keeping these factors in mind, engineers can more efficiently and successfully bring products from concept to completion. It is the goal of this work to examine any current strategies and see where and why they fall short, as well as to present an initial attempt at a method to strategically approaching engineering prototyping.

The Business Approach

While businesses recognize the importance of innovation, the creative design process, and the usefulness of prototyping in successful product development, management does not necessarily understand how to then go about creating actual physical prototype(s). Management is more focused on the logistical aspects of keeping a project successful, than on the actual processes the engineers may be using to develop a successful product. Managers may understand that many tools exist to aid in the prototyping process, and that proper use of these tools can make the prototyping process more efficient. They may look at successful companies and note that they use certain processes. However, any attempt at direct replication of one successful company's approach may not be as optimal for another company.

While it is often played off as having to be an entire "corporate culture" that cannot be duplicated, we believe the reasons for this approach failing are far simpler. Successful companies have experienced engineers in their labs who have a certain domain knowledge, even if they don't have a documented process they adhere to when developing prototypes. Because this is not recognized in the current project management documentation, we believe this to be a large part of the aforementioned "culture." Without a similarly knowledgeable engineering team to implement the strategies, it would make sense as to why one company's strategy would not translate well to another.

Many books on corporate innovation and project management practices provide examples of how prototyping can lead to either disruptive or sustaining innovations, but few embrace this as being worth more thorough examination. Some throw in a few anecdotal stories about the importance of prototyping[4,5,6]. Others go a little more in depth into what prototyping is and why it is useful, but stop short of any kind of technical detail or rationale for strategic approaches to prototyping[7]. For the most part, prototyping is recognized as a tool for successful product development and it is then left up to the engineering teams to determine how to get from concept to final product.

What is most telling about how prototyping is viewed by management are the books that focus on it the most. These books extol the virtues and importance of prototyping, but fail to provide any type of logical process teams go through to create a successful prototype. When it comes to discussing the actual creation of prototypes, it is consistently described as a one step process. Kelley, when describing the innovation process at IDEO, stresses the importance of prototyping: "Never go into a meeting without a prototype," and includes an entire chapter devoted to prototyping[8]. However, the work never goes into depth about strategies the teams employ when creating prototypes. For the most part we see phrases like "bang out a quick prototype", "knock out a prototype", or "work up a quick prototype."

For a successful company with many experienced engineers who are focused solely on rapid product development, prototyping may appear to be that simple. If prototyping really were that easy for the majority of companies, it is likely that the average failure rate across industries would be lower, and firms like IDEO would not be viewed as relatively unique. Clearly, the work is not addressing a key point: the real complexity of prototype development. In order to make prototyping seem that simple, IDEO's engineers must have a strategy to understand how to optimally approach each prototyping effort, so that it can be completed quickly and efficiently. In other words, they employ some sort of internal strategy, officially documented or not, that dictates how decisions concerning prototype creation are made.

Even the most in-depth books, such as works by Thomke or Schrage, only minimally develop overall prototyping strategy[9,10]. They recognize that approaches like parallel development or iteration are useful in expanding a prototype's feature set instead of trying to incorporate all features at once. Points are made about how software simulation and rapid printing are powerful tools for making prototyping cheaper and conceivably less costly in terms of resources. However, the works often seem to treat these as ideal solutions instead of a part of the process. Such technologies have their place, but as these works are geared more towards informing project management, they do not go into much depth as to what that place may be.

One example given by Thomke is the use of automobile crash simulation software to replace the use of physical prototype testing. The feeling from the book is that the only reason simulation software shouldn't replace physical prototyping completely is because of a lack of current (for the time) computing power and government regulations requiring the destruction of physical models for safety testing. While there is no denying the usefulness of this software, and its impact on discovering potential issues early in the design process, there is a point when car makers must move to destroying real world prototypes and gathering data from those to inform better decisions. One can assume that it is for reasons like this that we have recently seen Lexus release a new crash test dummy, capable of gathering almost 17,000 times more data than a traditional crash test dummy. It was likely easier, cheaper, and faster in this case to develop a physical model with enhanced sensitivity versus adding an additional 2 million points to a finite element analysis of a collision.

Other works on product development also fail to adequately address prototyping strategy as an important part of a successful creation process. In Clark's study of product development in the automotive industry, the author recognizes that innovation and an ability to bring a solid product to market quickly is key to being successful[11]. It recognizes that prototyping is important, mentions a variety of ways prototyping efforts might fail, and gives brief descriptions of how certain parts may be prototyped. However, the main concerns with prototyping are traditional management focuses: time, cost, and functionality. The work does little to look into why certain methods are used or successful, and leaves that for engineers to figure out.

There are a few papers that do an excellent job of addressing specific areas related to engineering aspects of prototyping. While they are more geared towards helping project management understand the engineering aspects, rather than specifically guiding engineers, they do touch upon some important concepts in prototype development. Work by Dahan and Mendelson[12] provides an in-depth analysis of the benefits of parallel versus sequential prototyping in environments with various resource restrictions. They find evidence supporting sequential design in cost constrained environments, and parallel design in time constrained environments. They also find support for parallel prototyping when experimentation costs decline, or when upside profits are uncertain.

Work by Thomke and Bell[13] provides an analysis of sequential prototype testing and the value of low versus high fidelity prototypes, but in the context of monetary cost. They find that significant cost savings can be incurred by performing more tests with multiple low fidelity prototypes, versus fewer tests on a fully functional prototype. This holds true as long as the test results provide partially overlapping data and the fixed cost of any given test is low.

A similar paper by Thomke[14] looks at the benefits of modern prototyping tools, and suggests some basic guidelines as to when it might be beneficial to pursue certain development avenues over others. His paper makes an argument to management that the optimal cost and time savings come with the proper use of multiple technologies, such as using simulation software to develop a solid design and rapid prototyping technologies to test it. He also notes the importance of effective management when the change in experimentation modes requires multiple distinct groups, such as CAD designers versus shop technicians. This extends both to making sure that the project transitions easily from one group to the next, as well as ensuring that development resources are properly distributed.

The only comprehensive "business" study we found that examines a variety of prototyping situations and then outlines a series of best practices is a recent release from the RAND corporation[15]. In this work, four decades of DoD prototyping projects are studied, and a series of findings are derived. While the paper is geared towards informing project management, the focal point of this work is to determine what kind of environment must exist for prototyping strategies to be effective. It touches on some of the key factors of prototyping that we believe are missing from current documentation. The suggestions are as follows:

- Results Are Used to Inform Key Program Decisions
    - Make sure that prototypes are built towards the goal of meeting minimum design requirements, and that information gathered from prototype testing is useful. If it is apparent that objective requirements cannot currently be met, it is not wise to proceed with prototyping efforts.
- The Prototype Is Designed to Demonstrate the Critical Attributes of the Final Product in a Realistic Environment
    - The goal of a prototype is to prove that the final product is viable in the real world. Besides meeting performance requirements, this also includes meeting design requirements, such as the ability to properly integrate with existing systems.
- Prototyping Strategies and Documentation Are Austere
    - Extra features are nice, but they represent extra resource cost that may not be desired. Prototypes are intended to be focused on determining unknown quantities; features that are known to likely work can be included later on in the process, if requested.
- There Should Be No Commitment to Production During the Prototyping Phase
    - Being experimental, prototypes may end up with test results that indicate a final product is not yet ready to be developed, given current technologies. If a production commitment has already been made, this could put the project in an

awkward position and lead to further development attempts or even production of a product that should not yet be developed.

- No Additional Requirements Are Added or Performance Increases Expected
    - Prototypes are designed and built around meeting a specific set of criteria. Increasing or adding requirements partway through the design process is dangerous. Instead of starting the design process from scratch, teams may feel pressured to just tweak or add on to what has already been developed, leading to sloppy results.

Additionally, it is noted that prototyping teams should be small teams of highly skilled individuals who are allowed to work with little disturbance. This allows the teams to make decisions internally, and prevents the last two conditions from jeopardizing the project.

It is possible that project managers' think success can be achieved purely through resource management. It may also be possible that this is a consequence of habit: their approach has worked 60% of the time so far, and any change could just as easily lower the success rate as raise it. While the work done concerning resource management and business strategy is commendable and just as important in successful product development, it needs to be combined with the technical knowledge of engineers. Engineers should have the knowledge required to determine how to best then use the resources they are given, via the wide variety of prototyping methods they have at their disposal. With the combined body of work on resource management and the knowledge of how to properly utilize these resources, the likelihood of a successful prototyping effort should increase.

The Engineering Approach

While one might expect the engineering realm to dedicate equal time to the importance of prototyping as a whole process, this is not the case. The vast majority of works either deal with concept ideation and design methods, or use of the virtual and physical systems (i.e. CAD modeling or CNC machining) to bring an idea into a visual or physical realm where analysis can be performed. While these are important steps in the product development process, there appears to be a lack of existing documentation that defines how to optimally move from concept to final product. There also appears to be a lack of work that addresses some of the resource issues that are mentioned in project management literature.

Some of the best examples of engineering approaches to prototyping are found in collegiate focused product design textbooks. While each only provides a limited focus on prototyping in comparison to the design process leading up to prototyping, what they do present is an excellent starting point. In Otto and Wood's book[16], prototyping is looked at in multiple chapters that cover various analytical modeling techniques, physical prototype development processes and suggestions, and proper testing strategies to ensure that physical models meet requirements. The authors recognize that while non-physical modeling is certainly important, designers must move on to the development and testing of physical prototypes.

The chapter on physical prototyping provides a variety of questions for development teams to consider when moving into the physical realm, as well as classifying prototyping efforts into groups that relate to purpose or overall completeness in comparison to a final product. It also details some of the various uses of prototypes, such as obtaining customer feedback, demonstrating design requirements, determining feasibility, scheduling, interfacing, and system modeling. Much of the chapter is devoted to information on prototyping materials and processes, with a large portion being devoted to the rise of rapid prototyping technologies.

Finally the chapter ends with a suggested basic method for physical prototype design, and a case study that implements this method. In this section they give suggestions for a prototype design procedure, some guidelines for prototype development, and a sample template for keeping track of design decisions. While the information provided in this book is valuable and it makes an excellent attempt at strategizing prototyping, it is not the main focus of the authors' work. It provides excellent building blocks for future work and gave many ideas towards the work that we present later in this paper.

The second book to provide an excellent initial attempt at prototyping strategy is a work by Ulrirch and Eppinger[17]. While it covers some of the same material as Otto and Wood, such as prototype methods and materials, a discussion on the usefulness of physical versus non-physical prototyping methods, and various uses of prototypes, this work has an increased focus on approaching the prototyping process strategically.

While Otto and Wood detail out many different classes of prototypes and approaches, Ulrich and Eppinger look for more general traits that describe the prototyping process. It is this general approach to looking at major factors in prototyping that makes this work particularly useful.

For example, they chart out the prototyping process of a laptop trackball in a two dimensional space, where the x axis is determined by the level of functionality of an effort and the y axis is the transition from mathematical modeling to physical product. While the example is limited in scope, and shows a fairly linear line from a focused analytical model to a comprehensive physical prototype, they note that that designs can fall anywhere on the graph. The only caveat given is that it is generally unfeasible to produce a comprehensive non-physical model. This may not be true for designs where the costs of any physical prototypes are so high that none can be made. A recent example of such an exception is the complete CAD modeling of the next class of US Navy super-carrier by Northrop Grumman[18].

There are also only a few works which look at management side issues from an engineering standpoint. Until recently, there were very few attempts made at considering the importance of resource allocation when prototyping. A traditional method for determining product cost is cost modeling, which is a summary of part costs, assembly costs, and overhead costs calculated off design specifications and materials lists. However, this approach does not work well in the prototyping phase, as few if any of these costs are set in stone. For new product development there is even more difficulty in developing a traditional cost model, as teams may not be able to compare part costs of prior art or competitors products. There has been some recent work into alternative methods of providing cost estimates at an earlier stage via regression analysis, but it is reliant on a large knowledge base of prior art for comparison, and degrades in accuracy as design attributes are added[19].

There have also been analyses performed on specific areas of prototyping, such as to determine the most cost effective approach to using certain technologies over others. One such study conducts a make or buy analysis when considering the use of rapid prototyping by a variety of companies in different resource scenarios[20]. While is it certainly beneficial to conduct such studies, they do not help inform our decisions as a whole and require a solid decision tree to get to the point where such an analysis is most beneficial.

Others have taken a very general approach to evaluating the effect of resource constraints on the design process[21]. This work is particularly interesting, and one of few works addressing the impact of multiple resource constraints. Participants were asked to complete a variety of tasks by designing and building structures to meet certain requirements. While the results certainly show that imposing resource constraints had a negative impact on the number of designs produced, it had the positive effect of reducing completion time of the tasks, likely due to limiting the number of available solutions. Another finding was that as task constraints increased, the number of solutions diminished naturally. By comparison, in the most complex task, the resource constraints had little to no effect on the number of solutions that participants created.

One interesting design valuation approach, by Rosen and Franck[22], is to evaluate the informational value versus the cost value of the prototyping effort as you go, to ensure that you are maximizing the amount of useful information gained at any given point. By using educated decisions to ensure that optimal prototyping techniques are used, a design team could shorten the design lifecycle of a product and stay on or under budget.

As a subset of an overall prototyping strategy, there is some work that goes into detail about choosing specific methods, such as what kind of rapid prototyping method to use, once one has decided to use rapid prototyping and has evaluated a variety of criteria[23]. While good information, the knowledge gained here is very specific and assumes that teams have already done all the work to correctly identify that rapid prototyping is the proper course of action.

<u>The Importance of Prototyping</u>

A particularly interesting group of papers that have been published recently outline the importance of prototyping in the design process by studying the effects of prototyping on the design process and the effects of prototyping on the designers.

The first, a study related to engineering and of positive impact for the management side[24], reached publication just before this paper's submission. It details the psychology of prototyping from an engineer's standpoint, confirming academically what had been colloquially suggested to the authors over the course of literature research. The results of the study detail the idea of positive reinforcement via the use of "low fidelity", or what we would consider functionally scaled, prototypes. By creating a large number of scaled prototypes at a low resource cost, creators are able to rapidly conduct user evaluations of the product as well as start understanding trends in user preference at an early stage in the process. While the impact of scaled prototyping has been previously detailed, this supports the idea that it is not only beneficial to the product to engage in this practice, but to the design team as well. The authors discovered a threefold impact on the psyche of the design team:

1. Failure is reframed as an opportunity for learning
2. A sense of forward progress is fostered
3. Beliefs about creative ability are strengthened

This concept meshes well with the findings of the earlier RAND report: breaking down a project into simple steps can increase overall efficiency of a team and create a high quality end product.

The second paper provides a look at the effect of both group work and design environments when prototyping, in regard to design fixation[25]. The study looks at design fixation in both “amateurs” (non-engineering students), and “designers” (engineering, design, or architecture students), individually, in real groups, and in nominal groups. It also studied the impact of design fixation when available design environments were limited to virtual environments versus virtual and physical spaces. It was found that groups are most useful when the design environment was limited and that design performance across the board became significantly better with the introduction of a full design environment, which allowed for physical construction and testing of a prototype.

Another recent paper also supports the idea of prototyping being critical to the design process and the reduction of design fixation[26]. In the experiment, student groups were given different tasks across multiple design stages. Some were allowed to build one or more prototypes early on and then reflect upon what they had built, some were allowed to consistently improve their prototypes, some were only allowed to start working on physical prototypes at the end, and some were not allowed to build any prototypes. All groups received technical critiques of their designs in between the three design stages. The overall takeaway is that early prototyping efforts that are non-continuous are likely to quickly settle on one concept and perfect it. Allowing for constant prototyping allows a team a chance to develop entirely new concepts with time to evaluate them properly. Late prototyping leads teams to either stick with a design or completely change designs, based on feedback, until they can actually build one, and then only do tweaking on any design at the end. Not allowing prototyping is likely to lead to no changes or small tweaks to the initial concepts, regardless of any potential faults.

These papers all support the idea that prototyping is not only beneficial to the product itself, but to the teams of people working on them as well. It allows for increased confidence, the potential for brand new concepts based off results, or at the very least, time to tweak a product towards perfection.

Theory

From this review, three important points are derived:

1. Management oriented prototyping strategies are generally not made to address prototype creation at the engineering level.
2. There are few engineering oriented prototyping strategies, none of which address the full scope of decisions associated with a full prototyping strategy.
3. Prototyping is a beneficial process that is worth more consideration and further examination.

Currently, the success of a prototyping effort depends on the expertise of those attempting it. The longer an engineer has been prototyping, the more likely it is that they have gained knowledge of what may or may not work: how to approach the creation of certain elements, what kind of resource usage these tasks may require, whether or not to anticipate issues in the future when using certain processes, etc. This experience allows them to make strategic decisions earlier in the prototyping process. Unfortunately, this experience tends to be gained either slowly over time or through trial and error, which can be very costly. In addition, if the product development environment changes, (for example from sustaining oriented to disruptive oriented) this experience may no longer be relevant to understanding the optimal prototyping strategy.

Our work aspires to emulate as much of this experience as possible by forcing a team to strategically evaluate prototypes on a variety of different aspects from an early stage. By doing so, we hope to be able to create success at any level of expertise, and remove the existing time/experience requirement to successful prototype generation. This would be particularly useful in early stages of engineering education and would allow students to enter into product creation activities (such as senior design projects) with a significant body of knowledge and understanding of the processes involved.

Our hypothesis is that if proper strategic measures are taken by engineers early on in the prototyping process, prototyping efforts are more likely to both be efficient and successful. While it is obvious that having a well laid out strategy may be useful in preventing project failure or resource overrun, it should also be noted that a good strategy may equally benefit successful endeavors by making them that much more efficient.

To this end, we have come up with a list of what we believe to be the major factors to be taken into account when considering prototype generation. By considering these elements and developing a prototyping strategy, we believe that engineers can increase the success of prototyping efforts. Not all efforts will need to take all factors into account, as not all factors will apply to every prototyping effort, but this list is intended to be generally applicable to any prototyping endeavor.

Factors in a Prototyping Strategy:

1. **Prototypes can be of a single subsystem, of a set of subsystems, or of the entire system**

   When approaching the creation of a large system, it may be beneficial to break the effort down into smaller subsystems that can each be approached with optimal strategy.

2. **Prototyping multiple concepts in parallel vs. prototyping only a single concept**

   While only one or two concepts will likely eventually be chosen to fully developed, the development of multiple prototypes at an early stage can help provide critical feedback.

3. **Iterative prototypes vs. only 1 prototype per concept**

   This factor considers whether or not it makes sense to tackle a prototype all at once, or to focus on ensuring that certain design requirements are met before adding others. This is useful when paring down the number of concepts to a final few, or interfacing working designs from multiple efforts.

4. **Prototypes can be virtual (analytical, CAD, FEA, CFD etc.) or physical**

   Complex analyses are generally more easily performed by computer than by hand, and development of a CAD model can translate into production benefits for both prototype development and final product manufacturing. However, some of the best feedback a team can get for product development is to have a physical product available for user interaction.

5. **Prototype manufacturing can be outsourced, rapid prototyped or completed in-house**

   Outsourcing can be resource heavy in terms of cost and time without the item, but frees up the team to work on other aspects of the project and provides access to resources that may not be available internally. Rapid prototyping technologies allow for fast production of parts for evaluation, but available materials are limited, which may not allow parts to be fully evaluated against design requirements. Finally, prototypes may be completed in house, assuming the resources and skill are available. This option tends to be cheaper in cost, but more time intensive for the team.

6. **Prototypes can be physically scaled**

   With certain large products, such as ships and airplanes, creating a full size prototype may not be feasible until the final stage of prototyping, where any full-scale prototype is basically a final product. Additionally, for certain testing methods, such as wind tunnel testing, teams may not have equipment large enough to test a full size device.

7. **Prototypes can be functionally scaled**

   It may be beneficial for teams to design prototypes that contain only a few design requirements at a time, to be able to properly ensure and evaluate the successful implementation of requested features. This can allow for easier testing of prototypes and a more robust final product, but may lead to issues when interfacing multiple prototypes into one final design.

8. **Prototypes can use similar or different materials than the final design**

   Because prototypes have the advantage of not having to meet final design requirements at all stages, some leeway may be given to material selection for prototype development.

9. **Prototypes can use similar or different manufacturing and assembly techniques than the final design**

   With the rise of rapid printing and rapid tooling, teams are able to decide if they want prototypes to be manufactured and assembled in a similar fashion to the final products.

This list of factors is focused on the elements that comprise important engineering decisions regarding the progression from prototype concept to reality. There are secondary factors, such as resource usage, that tend to traditionally fall more on the project management side. While these resource factors should be taken into account, it should be as an aide to determining the weight of the primary prototyping factors.

Method

While identification of the main factors of prototyping is useful, we believe that it is also imperative that a process for evaluating a project against those factors be developed. In this way, we can determine which factors will have the greatest impact on a prototyping effort and create a tailored prototyping strategy for each project. By evaluating each project with a set of questions that address prototyping issues at a universal level, we hope to allow for a basis of comparison that will help dictate the likelihood of success in any given endeavor.

We have developed an initial list of questions, based off the identified factors, for an engineering team to review. By answering these questions, the team should be able to determine which factors will impact the project most, and identify a strategy that best meets the requirements of the project against the resources available. We have also developed a supplementary matrix in which to organize results. An example matrix will be provided in step 2 of the process. With the help of this matrix, our teams were able to easily identify which prototyping factors were most relevant to their prototyping efforts, and were able to develop a concrete strategy for moving forward with prototype development.

For the purposes of reviewing these questions, we will assume the case of our team of students: they had reached the end of a design ideation phase, but had yet to pick which concepts they want to focus on creating. It was found useful to consider all questions, even those that appear unnecessary, as it ended up being found optimal to further break down previously planned efforts.

Step 1: Comprehensive evaluation of individual prototyping endeavors

Prototyping Technologies

When exiting the concept stage, it is necessary to first determine the best way to go about creating the product. The assumption here is that work is being done towards final, comprehensive physical prototypes, but there may be the exception where it does not yet make sense to move in that direction. This may be the case in staged projects, where resource limitations prevent physical production until a review of the work up to that point can be completed.

1. **Is an _analytical_ prototype a possibility? If so, how difficult is the analysis and which design requirements would it potentially verify that this concept meets?**

   Analytical prototypes are useful, and can often be used to develop some quick performance figures.

2. **Is a _computer simulation_ prototype a possibility? If so, how difficult is the simulation to create and which design requirements would it potentially verify that this concept meets?**

When creating individual parts for future use as production references or rapid prototyping templates, computer simulation via CAD drawings is one of the best prototyping techniques, especially since models can often easily be subjected to analytical modeling software.

3. **Is a _rapid prototyping_ technique applicable?**

   Rapid prototyping technologies are extremely useful for creating quick physical models for rapid feedback and design iteration. Technologies can include 3D printing, laser sintering, stereolithography, rapid CNC machining, next-day injection molding, etc.

Resource Usage

Traditionally left to consideration by management, resource allocation estimates are extremely useful for keeping projects on track. If a design looks potentially unfeasible or even particularly resource heavy at an early stage, there is a greater likelihood of resource overrun in the long term.

4. **Can I _outsource_ the construction of a prototype?**

   Outsourcing removes work from the control of the team and eats up extra resources, especially in terms of cost and time. However, outsourcing can provide access to other production techniques and methods which may better meet design requirements than available internal production capabilities.

5. **What percent of the overall prototyping _budget_ (financial allocation) will each proposed prototype expend?**

   While it may be difficult to assign hard numbers to each prototype at an early stage, it is important to be able to estimate resource allocation. By looking at how much budget a team would be willing to apply to a given prototype, they can get an estimate of how many prototypes they can develop, from a financial standpoint.

6. **What percent of the overall amount of _human resources_ (in person-hours) allocated for prototyping will each proposed prototype expend?**

   Similarly, it may be difficult to quantify the exact man hours to be expended on a prototyping effort. If a ratio can be decided for roughly how much time should go to each effort, the number of man hours allotted can be determined based off any given deadlines. It can be noted that not all processes are difficult to quantify: for example, if using a rapid prototyping technology, the amount of time it will take to create a component of a given size can be determined by the speed of the machine.

Design Requirements

Every project should strive to meet design requirements, so the focus here is to split the requirements into minimum and preferred requirements. A prototype should be able to meet a minimum standard, but testing the same requirements across multiple prototypes is often a wasted effort. Additionally, we look to bring focus to the testing of failure modes. Ensuring that this is taken into account at an early stage helps make sure that prototypes undergo rigorous evaluation.

7. **What is the potential that the proposed prototype will achieve the threshold *design requirements*? What about the objective requirements?**

   This is one of the more important questions a team should be able to answer even from an early stage. Going over a list of design requirements and seeing which prototypes will meet minimum or preferred requirements is critical to ensuring that resources are not wasted on an exercise that either does not achieve a design requirement or provide unique data towards fulfilling a design requirement.

8. **Which *design requirements/failure modes* will I be able to test using this prototype? Which ones won't I be able to test?**

   While confirmation of data is useful, making sure that testing is not repeated unnecessarily is desirable. It is not required to know or test all possible failure modes in order to begin, but it is helpful to keep in mind.

9. **Does the proposed prototype demonstrate critical *interface issues* within the system?**

   Interfacing can include things like systems of measurement, proprietary types of couplings, and software languages, as well as the ability for product purchasers to effectively make use of the system.

Scalability

Traditionally, this is what would be referred to as a focused prototype. However, prototype scalability has multiple aspects that we feel should not be lumped together, as scaling certain aspects will fundamentally change the way data about a prototype can be gathered.

10. **To what extent would you save resources in terms of both human-hours and cost with a *dimensionally scaled* prototype? Which requirements/failure modes would you lose the ability to test if you use a dimensionally scaled prototype?**

    For many larger items, it may make sense to create a smaller physical model, if for no other reason than an inability to produce a full size prototype quickly or easily. Examples may include models of buildings or ships, or airplane models build for testing in wind tunnels.

11. **To what extent would you save resources in terms of both human-hours and cost with a *functionally scaled* prototype? Which requirements/failure modes would you lose the ability to test if you use a functionally scaled prototype?**

    It is often not a good idea to tackle all design requirements in one prototype. Instead, it may be helpful to focus on specific important requirements independently, and integrate them into one prototype in a later iteration. Examples of this may include a full size auto or airplane body for final aerodynamic testing, or a variety of non-functional cell phone bodies for ergonomic testing.

Production Flexibility

Final designs and materials may not yet be known, and it is difficult to evaluate a supply chain for parts that do not yet exist. However, it is important to recognize that a great prototype which cannot be easily duplicated could end an entire project, wasting all resources thus far invested, or result in a product poorly put to market. Our aim here is to make sure that teams at least take future production concerns into account, even if it is to make them aware that the current prototyping methods are not feasible for final production.

12. **To what extent would you save resources in terms of both human-hours and cost by using *different materials* for the prototype than you plan to use for the final system? Which requirements/failure modes would you lose the ability to test if you use these different materials?**

    While it may be ideal to work with the final materials, they may also be costly or difficult to obtain in the desired form.

13. **To what extent would you save resources, in terms of both human-hours and cost, by using *different manufacturing and assembly processes* for the prototype than you plan to use for the final system? Which requirements/failure modes would you lose the ability to test if you use these different manufacturing and assembly processes?**

    Because many prototypes are often handcrafted versus mass produced, engineers need to decide how closely they would like various stages of the prototype to emulate a final production model.

One important concept that has not yet been addressed is that of prototype partitioning. While it may often been seen as common sense to break down product creation into manageable pieces, it is not always seen in practice. Answering the above questions can help determine whether or not development of a particular idea needs to be broken down further. Prototype partitioning can either take place by iterating on one design multiple times, developing multiple designs separately (generally concurrently), or by breaking the project down into completely separate subsystems. When breaking a prototype into smaller systems, it may be wise to repeat the strategy process again for each subsystem, to make sure all details for each are properly reviewed. Moe provides additional insight into this partitioning process[27].

Generally speaking, if multiple ideas are good development candidates or if multiple design requirements/failure modes can be tested independently, concurrent development is a good choice. If multiple production methods or materials are to be used, such as rapid prototyping, or if prototype scaling is to be used, it may be wise to focus on iteration of one or two ideas.

Step 2: Visualization and organization of results

By answering the question set for each concept, we can determine the weight of each prototyping factor on each endeavor and ensure that efforts fall within reasonable resource usage. By repeating the question set for all concepts and sub-systems identified as needing partitioning and entering data into a single strategy matrix, we can get a visual representation and comparison of all ideas, along with total resource use, that allows for selection of the best concepts for development.

The included matrix (Table 1) is a sample project, outlining two different prototyping concept proposals.

Step 3: Comparison and evaluation of results

When reviewing this matrix, we see two concept development possibilities. The first concept is slated to undergo a simple analytical evaluation to ensure feasibility, and then to be produced (possibly by outsourcing at a higher cost and reduced time) as a fully functional prototype. The second concept undergoes further computer simulation and CAD modeling, and then has the physical production broken down into two parts, one which can be tested in-house with rapid prototyping techniques, and the other which has the option for outsourcing construction. Both options are feasible to produce with given resource constraints, but would use up most of the available resources, with little room for any extra work that may be discovered as needing to be done. Both also test many of the same requirements and failure modes, indicating possible unnecessary duplication of efforts. It would be up to the team working with management at this point to decide if both concepts are worth developing and in what order, or if one should be chosen and perhaps expanded upon at the cost of some extra resources. In this case it might be advisable to choose one concept, but apply the ideas of both. Concept 2 could benefit from the already laid out testing phases, and then use the resources from Concept 1 to produce a well tested full prototype.

When looking at a product matrix, it is important to look for heavy weighting in any given category. While resource usage close to or over 100% may be obvious to avoid, other aspects may be less apparent. Too much outsourcing may lead to designs being difficult to change or update, and leads to parts spending a lot of time outside of the hands of developers, potentially leading to less hands on testing time. Rapid prototyping technologies are often “set and forget” but take a good amount of time to produce parts; time needs to be allotted for the creation of the parts, even when it does not directly affect the man-hours put in by the team. Using final materials and production techniques on at least one concept allow for production estimates to begin. Ensuring that all design requirements and failure modes are tested and meet minimum, if not optimal performance requirement is ideal, though it may not be feasible to include everything.

We believe the strategy we have developed can be applied at different points in the product development process, depending on the results desired. By applying our method at the end of the conceptual design/ideation phase, but before final designs are chosen, it can be used to provide an early analysis of prototyping ideas. This can help maximize the ratio of resource use to requirement and failure mode testing. By applying it once final designs are chosen, it can be used to create resource use estimates as well as ensure that certain production concerns are addressed. By utilizing it during design iteration, it provides the ability to evaluate actual resource usage against estimates and re-evaluate the selected prototypes. This mid-project evaluation can help expand or constrict the design space, stop development on prototypes that have proven to be inadequate, allow for further iteration on the best prototypes, and keep track of resource usage to know whether or not the project is proceeding as planned.

<u>Table 1</u>

Prototype Strategy Matrix

Prototype (identify if this is a full system or subsystem)	Type	% of $	% of person-hrs	Use Rapid Prototyping technologies?	Possibly Outsource?	Dimensionally scaled?
Concept 1 – iteration A	Analysis	0	10	No	No	N/A
Concept 1 – iteration B	Physical	30-50	20-40	No	Yes	No
Concept 2 – iteration A	CAD + Simulation	0	20	No	No	N/A
Concept 2a – iteration A	Physical	20	10	Yes	No	Yes
Concept 2b – Iteration A	Physical	20	10-20	No	Yes	No

Prototype Strategy Matrix (cont'd.)

Prototype (identify if this is a full system or subsystem)	Functionally scaled?	Which requirements are/aren't tested?	Which failure modes are/aren't tested?	Using same materials as final design?	Using same manf. & assembly as final design?
Concept 1 – iteration A	Yes	3 <2-9>	a-c <d-m>	Yes	N/A
Concept 1 – iteration B	No	1,2,6-8 <3-5,9>	e-i <a-d,j-m>	Yes	Yes
Concept 2 – iteration A	Yes	3,4 <1-2,4-9>	d-f <a-c,g-m>	Yes	N/A
Concept 2a – iteration A	Yes	6-9 <1-5>	j-m <a-k>	No	No
Concept 2b – Iteration A	Yes	1,2 <3-9>	a-f <g-m>	Yes	Yes

List design requirements in order of decreasing priority (include threshold and objective values)

1. Velocity (threshold = 30 MPH, objective = 50 MPH)
2. Power (threshold = 40 HP, objective = 70 HP)
3. …
9.

List failure modes in order of decreasing importance (from FMEA)

a. Frame yields
b. Gears strip
c. …
m.

Case study: Development of a Prototype Medical Device

During the course of literature review for this study, an excellent example of why prototype strategies are useful was discovered. While the primary focus of the paper was the prototyping of medical devices, a secondary aspect was the inadvertent discovery of why prototyping efforts can benefit from a strategic approach[28]. After creating a CAD model, a physical prototype was developed using rapid prototyping technologies. The intention of the effort was to create a functional prototype from the start, in order to shorten the product development cycle. However, it was discovered that the properties of the material used by the prototyping machine were incompatible with the desired results. The removal of support material was difficult, the resin too fragile for assembly, and the production method did not produce parts with the desired dimensional tolerances. The authors then decided to create the prototype entirely of CNC-machined polycarbonate. After this was completed, it was discovered that the polycarbonate's rigidity was too high to be able to functionally test the prototype. A third "hybrid" method, using a combination of materials and manufacturing processes (CNC machined polycarbonate and vacuum-cast polyurethane) was finally settled upon to create a functionally testable prototype. Finally, for a pilot production run, a fourth material, polypropylene was chosen for a variety of reasons.

This is a fairly simple example, and there were no real consequences of failure other than the delay in bringing the product to market (which, of course, can be critical), but it highlights a more prevalent issue in prototype development. While the experience gained was surely valuable, if the authors had been able to initially identify that certain materials or processes might not likely produce a viable prototype, the project could have been completed with a much greater efficiency. If this had been a resource constrained project, and a timeline had been created based off the availability of a functional prototype from the start, this project would have been considered a failure. Having to repeat the full prototyping effort three times in order to achieve the minimum functional requirements would not even be possible in a constrained environment.

If a prototyping strategy had been applied before physical development of the product, it is likely that it would have been discovered that different components required different materials and manufacturing processes. Based on that information, prototype partitioning could have been used to separate out the pieces needing independent evaluation. Even if this had not led to complete initial success, it would likely have provided partial success at an accelerated rate, which is looked upon with a lot more favor than a complete failure.

Initial Evaluation of our Method

During the course of the fall 2011 semester, we informally tested our theory and method with a mechanical engineering senior design class at the US Air Force Academy, comprised of multiple design teams, all with differing design projects. The idea was to gather qualitative data regarding the completeness of our current theory and use any findings to iterate on our process. The theory was given to all groups to work with and applied to as many teams as possible, regardless of where they were in the prototyping process. The goal in this was to see how applicable prototyping strategies could be when introduced at any given stage. While many of the groups could have progressed sufficiently without any additional strategy, at all stages of prototype creation our method was found to be useful in helping students realize forgotten, ignored, or previously unrealized variables. As expected, many of the groups had not considered resource allocation and had little idea of how to approach it, despite having limited time and funding. Many groups had also not considered testing potential failure modes of their prototypes, allowing for time to be spent on concepts which, once analyzed properly, proved to not be viable.

The focal point of this evaluation will be the work of one team working on development of a prototype electric land-speed vehicle. Due to the highly difficult and experimental nature of this project, it is setup to be a multiyear project that will incorporate the work of multiple senior design teams. Being a project with many costly components and a high potential for failure, the initial budget is extremely limited; the focus is on design and simulation of systems to verify the feasibility of the project. After initial research, it was decided that focus should be made on developing designs for a body, a power-train, and a cockpit. Other components such as steering, braking and suspension were deemed less critical of needing design work, and could likely be assembled from off-the-shelf parts in the future.

Because the entire project is, at this point, focused on concept generation and analysis instead of final product creation, much attention was given to the prototyping strategies in an effort to be as thorough as possible in prototype development. Unlike most other projects at this level, any mistakes will be passed onto the next project team, where the focus will likely be on generating physical prototypes out of the analysis and simulation done by this year's team. Any designs will not have time to be re-evaluated and will likely be taken at face value as being correct. For this reason, any oversight now could lead to total project failure for the next group.

Even though great care was taken initially to break down the project into subsystems that could be strategically approached, deficiencies were still discovered upon applying our prototyping strategies to the students' previous prototyping plan. By further breaking down the prototyping efforts and considering the prototyping factors, students were able to better understand the problems they were facing and approach them more tactically. During the course of discussion, it became apparent that the students would have to scale back some of their attempts, as attempting to physically model even one design of any one subsystem would likely consume the majority of the project budget. Attention was also given to planned simulations; while not consuming any money, they were highly time intensive and required use of software with which no student had any experience.

Having the entire prototyping strategy laid out at the beginning of the process also allowed students to re-evaluate their decisions as they went and, as such, easily re-evaluate the project as a whole with little effort. Students were able to realistically determine the ability of their simulations to meet design objectives. In the case of the body, it was determined that multiple body types could be successfully evaluated via computer simulation and scaled model wind tunnel testing. From the results of this, one body type would be chosen to pass on as a final design to the future team. With the drive-train, it was discovered that given available skill and resources, they could not conclusively verify that any proposed drive-train model would be able to meet minimum performance requirements. While analysis was still performed towards meeting the design goal, it will be up to the next team to take the current analysis and compare to real-world performance.

Conclusions

While much work has been done in the project management realm towards identifying the need for prototyping and prototyping strategies, current work either has little detail or is overly focused on using resource management to dictate the prototyping strategy. There is little work currently published in the engineering realm concerning comprehensive prototyping strategies. A few select texts touch on important concepts, but fail to address prototyping strategy on any comprehensive level. Some focused work has been done, but can only be used at specific points in the prototyping process. Recently, work has begun into evaluation of the effects of prototyping on design teams, and is showing it to be of great positive impact to teams and project success rates.

Our hypothesis is that by encouraging engineers to approach prototyping strategically, they can increase the chances of project success and increase the efficiency of successful projects.

We have identified what we believe to be the major factors in a prototyping strategy, and presented an initial method for weighing the value of each factor in any given prototyping effort. Using this method, which entails questioning and inputting decisions into a matrix, all stages of prototypes and prototype subsystems can be tracked and easily evaluated at the level of the whole project. This can help make engineers aware of potential project failure or resource overrun.

Initial qualitative evaluation of our method indicates that approaching prototyping efforts strategically has a positive result on the success of the prototype creation process, as well as promoting successful communication among teams and management. Further scrutiny of our prototyping factors and method by the community should be done to ensure that our list of important factors is comprehensive. Further research should be completed with an experiment designed around gaining qualitative and quantitative verification of our hypothesis. Comprehensive research should also be done in a professional environment to ensure that results are not skewed as a result of the academic nature of our prototyping environment and to make sure that the method is evaluated by subjects of all backgrounds and experience levels.

Acknowledgements

This work is partially supported by grants from the Air Force Research Labs (AFRL/RW, Eglin AFB, FL, AFRL/RXQ, Tyndall AFB, FL and AFRL/RB, Wright Patterson AFB, OH), grants from the Office of the Secretary of Defense (Office of Corrosion Policy and Oversight, Joint Ground Robotics Enterprise) and from the Defense Threat Reduction Agency as well as a grant from the NIST/TIP program, and, in part, by the University of Texas at Austin Cockrell School of Engineering and the Cullen Trust Endowed Professorship in Engineering No. 1. In addition, we acknowledge the support of the Department of Engineering Mechanics at the U.S. Air Force Academy. Any opinions, findings, or recommendations are those of the authors and do not necessarily reflect the views of the sponsors.

References

1. Jaruzelski, Barry, Loehr, John, and Holma, Richard, 2011, The Global Innovation 1000, strategy+business, Issue 65
2. Cooper, R. G., 1993, Winning at New Products: Accelerating the Process from Idea to Launch, Cambridge, MA: Perseus.
3. Barczak, G., Griffin, A. and Kahn, K. B., 2009, PERSPECTIVE: Trends and Drivers of Success in NPD Practices: Results of the 2003 PDMA Best Practices Study. Journal of Product Innovation Management, 26: 3–23.
4. Christensen, Clayton M., 2003, The Innovator's Dilemma
5. Dodgson, Mark, 2005, Think, Play, Do: Technology, Innovation, and Organization
6. Verganti, Roberto, 2009, Design-Driven Innovation: Changing the Rules of Competition by Radically Innovating What Things Mean
7. Martin, Roger, 2009, The Design of Business: Why Design Thinking Is the Next Competitive Advantage
8. Kelley, Tom, 2001, The Art of Innovation: Lessons in Creativity from IDEO, America's Leading Design Firm
9. Thomke, Stefan H., 2003, Experimentation Matters: Unlocking the Potential of New Technologies for Innovation
10. Schrage, Michael, 2000, Serious Play: How the World's Best Companies Simulate to Innovate
11. Clark, Kim, Fujimoto, Takahiro, 1991, Product Development Performance: Strategy, Organization, and Management in the World Auto Industry. Boston: Harvard Business School Press.
12. Dahan, Ely, H. Mendelson, 1998, Optimal parallel and sequential prototyping in product design, working paper, Stanford University Graduate School of Business, Stanford, CA.
13. Thomke, S.H., Bell, D., 1999, Optimal testing in product development, working paper, Harvard Business School, Cambridge, MA
14. Thomke, S.H., 1998, Managing experimentation in the design of new products, Management Sci. 44(June) 743–762
15. Drezner, Jeffery, 2009, On Prototyping, RAND Corp.
16. Otto, K.N., Wood, K.L., 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Upper Saddle River, N.J.:Prentice-Hall
17. Ulrich, K. T., Eppinger S. D., 2000, Product Design and Development, NY: Mc Graw-Hill.
18. Alpern, Peter, 2010, Visualize This, IndustryWeek, http://www.industryweek.com/articles/visualize_this_20809.aspx
19. Banga, Karan, Takai, Shun, 2011, Effects of design parameters in cost estimation and cost uncertainty modeling, ASME Design Engineering Technical Conference, Washington D.C.
20. Ruffo, Massimiliano, Tuck, Chris, Hague, Richard, 2007, Make or buy analysis for rapid manufacturing, Rapid Prototyping Journal, Vol. 13 Iss: 1, pp.23 - 29
21. Savage, Justin C. D., Moore, Carolynne Jane, Miles, John Christopher, Miles, Christopher, 1998, The interaction of time and cost constraints on the design process. Design Studies, 19 (2). pp. 217-233.
22. Franck, Christopher, Rosen, David, 2000, Measuring value of prototypes during product development, ASME Design Engineering Technical Conference, Baltimore, Maryland
23. Bernard, Alain, Deglin, Alexandre , Ris, Gabriel , 2003, An original approach for the memorisation and the generation of rapid product development processes, Rapid Prototyping Journal, Vol. 9 Iss: 2, pp.58 – 67
24. Gerber, Elizabeth, Maureen, Carroll, 2011, The psychological experience of prototyping. Design Studies, In Press: 1-21.
25. Youmans, R.J., 2011, The effects of physical prototyping and group work on the reduction of design fixation, Design Studies, 32, 115-138
26. Kershaw, Trina, Holtta-Otto, Lee, Yoon Soo, 2011, The Effect of Prototyping and Critical Feedback on Fixation in Engineering Design, Cognitive Science Society, CogSci2011 Conference
27. Moe, R.E., Jensen, D.J., Wood, K.L., 2004, "Prototype Partitioning Based On Requirement Flexibility," ASME Design Engineering Technical Conference, Salt Lake City, UT
28. Yeong Wai Yee and Yong Ming Shyan, John, 2008, Hybrid approach in prototyping functional medical safety devices: A case study, Virtual & Physical Prototyping, Vol. 3 Issue 1, p41-47