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Design Prototyping Methods

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Dedication

This work is dedicated to anyone who finds benefit in its content.

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Design Prototyping Methods

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Product development is often modeled as a cycle between phases of designing, building, and testing. This work will explore early stage build efforts of product design, which is also known as prototyping. Prototyping is a critical determinant of product success. Research shows that different approaches to prototyping can greatly affect design outcome. This work provides an integrated overview, and expansion of the existing work on design prototyping methods. Following the introduction, an extensive literature review of design prototyping tools, techniques, and methods is provided. These sources are indexed and comparatively reviewed. The capabilities of a novel hybrid prototyping technique is explored through a design case study. Next, insights from the review are integrated in a context independent prototyping strategy method. The method is developed with heuristics extracted from the literature, and additional insights from experimental studies. The technique is then experimentally evaluated. Finally, results of an extensive study of an online design repository are provided. The results include five key principles for prototype design and fabrication. The presence of these principles in the repository is validated through a novel crowd-sourced online study. The outcome effects of deploying these principles to design teams is experimentally evaluated. Overall, this research provides a guide to prototyping which includes a systematically indexed

review and comparison of the existing work, as well as a novel method, and principles for design and fabrication.

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Chapter 1: Introduction

The product development cycle is often modeled as an iterative loop through designing, building, and testing [1]. The early stages of build and test, in this cycle, are typically referred to as prototyping. A prototype is a pre-production representation of some aspect of a final product or design. Prototyping and design have been interwoven from antiquity through the present. Michelangelo and Palladio presented physical models for communication and planning [2]. Henry Ford's model T was the result of extensive prototyping efforts [3]. Dyson has stated that the commercially successful bag-less vacuum design was achieved after 5,127 prototypes [4]. Sensitivity analysis has also identified that prototyping is a key driver of design outcome [5]. The importance of prototyping could be said to be well known. Despite this, formulation of a well-planned prototyping effort remains a complex challenge. Many designers state that prototype planning occurs according to experience or intuition. There are limited tools to guide the development of prototyping efforts or to give insights on how to design and fabricate prototypes with higher efficiency. The research opportunity is found in the need to define, evaluate, and expand various techniques and principles for design prototyping that systematically enable innovative design.

The primary objective of this research is to identify, evaluate, and expand upon methodological tools and techniques for design prototyping. The primary objective is evaluated through four specific research objectives which map directly to the research projects covered in Chapters 2-5.

- Index and evaluate existing methodological tools and individual techniques for design prototyping and related empirical research findings.

- Employ a design case study to evaluate the effectiveness, as measured by model accuracy and cost, of a hybrid of two individual techniques.
- Evaluate the effects of deploying individual techniques on prototyping outcomes such as performance and cost expenditure; and determine outcome effects from employing an integrated strategy method to design teams.
- Explore DIY design repositories to search for potential prototype design and fabrication principles, to provide insight for the relatively open research issue of methods to achieve low cost, rapid, functional prototype embodiment; and to evaluate the outcome effects of deploying such principles to design teams.

Prototyping includes several outcome objectives. Refinement is perhaps the most commonly cited objective of prototyping [6]. Other commonly cited direct objectives of a prototyping effort are communication and usability testing, or design exploration and validation [7-10]. While indirect objectives, from reflective observation of the prototyping process itself, include increased knowledge of the design space [11], and clarified design requirements [12]. There is a substantial body of information regarding, objectives of prototyping, the relationship of prototyping and the design process, strategic techniques, and fabrication of prototypes. There is a need, however, to index the available research for comparative review. Chapter 2 provides an overview of prototyping literature. This review is constructed to provide indexed overviews of various subtopics in prototyping, illustrative examples for each individual technique, and empirical data regarding each technique [13].

It is also possible to evolve and combine individual techniques to form hybrid techniques. A hybrid technique involves the simultaneous implementation of two or more individual techniques in one prototype. Several projects have explored hybrid techniques for prototyping. An example is a mixed physical and virtual prototype [14]. A mixed prototype can enable iterations on subsystems as well as obtaining system level simulation information when all of the subsystems are not prototyped on a common platform. An example would be if the designers had developed a physical prototype for an automobile steering column, and a virtual prototype of the chassis and engine [15]. One open opportunity is to develop and evaluate additional hybrid prototyping techniques. Chapter 3 introduces a novel relaxed requirement virtual prototyping method via a design case study. The method is capable of providing normalized comparative ranking between competing designs with drastically reduced computational cost as compared to a full fidelity finite element model virtual prototype [16].

Individual and hybrid techniques can be used to achieve a variety of design outcomes. For many design efforts, however, the designer pursues several different prototypes. Therefore, the designer must partition the design problem and map it to an overall strategy. In other words, a series of choices need to be made regarding how the prototype will be made, and what information it will be used to gather. Careful planning of a prototyping strategy is required [17]. The need for this planning is because partitioning may influence the outcome of the prototype, specifically with regards to what is learned [18]. The scope of this plan may include the type of testing the prototype will undergo, as well as how it is constructed with regards to variables such as fidelity or scale [19]. There is an opportunity to explore prototyping strategies and compare the outcomes of various techniques. Chapter 4 pursues additional literature review on a subset of potential techniques. This information is integrated to develop a systematic strategy formation method. The individual techniques, and the pursuant method are experimentally evaluated [20]. The method provides an expanded dimensionality of the prototyping space, Figure 1.1, This framework is more comprehensive than the traditional stage gate definition of a prototyping strategy (from proof of concept, to alpha then beta level testing) to define a space with parallel concepts, multiple iterations, and fidelity properties of each individual prototype. The strategy method provides a tool to aid designers in navigating this space.

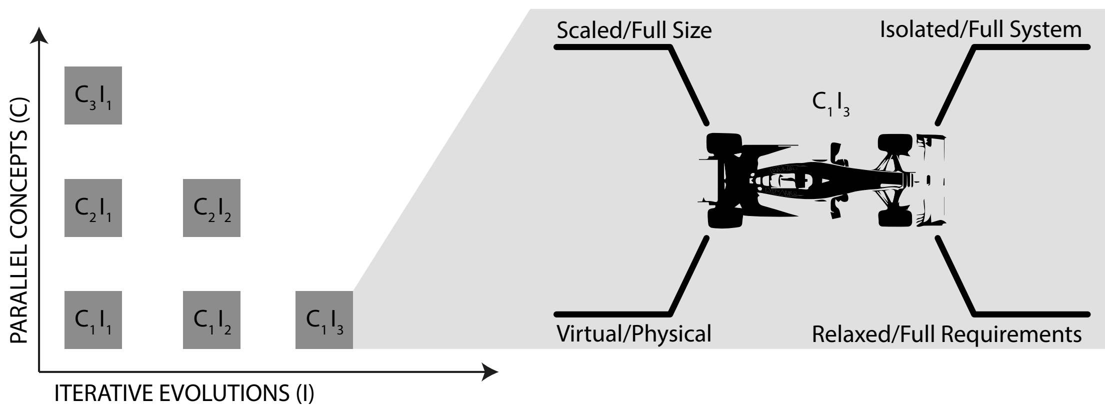


Figure 1.1: Schematic representation of the expanded design prototyping space. With six independent strategy variables.

A design strategy can form specific design goals and pathways for the overall effort. Once a strategy has been developed, the designer explores the detailed design of the prototype, including plans for fabrication. Design principles can offer a unique opportunity to guide this stage of prototyping. Principles are fundamental to the engineering process [21]. Principles can relate key insights from large data sets in compact form [22]. They provide aid in the solution of a problem, but may not directly provide a solution themselves [21]. Principles provide a necessary contextual flexibility required for prototyping methodologies. A prototyping method should be relevant to general design problems. There is an opportunity to explore and develop principles for prototype design and fabrication. Chapter 5 provides results from an extended empirical study of a prototype design database. The study consists of systematic extraction of principles for prototype design and fabrication. These principles provide avenues for developing highly functional prototypes with lower cost and effort [23].

As indicated by the summary and motivation above, an objective of this research is to develop an overview of the state-of-the-art design tools, methods, and techniques for prototyping. Previous research has identified a number of individual techniques to achieve specific outcomes from the prototyping process. Several studies have also identified the impact of various factors on design outcome. These studies explore factors such as time spent prototyping and the emergence of fixation. A novel relaxed requirement virtual prototyping method is presented, which demonstrates the potential of hybrid prototyping techniques. This study synthesizes existing research on prototyping methodology. This synthesis in turn leads to development and evaluation of an integrated prototyping strategy method, which guides development of an overall prototyping effort, leading to enhanced efficiency and outcome. The relatively open opportunity of determining principles for design and fabrication of prototypes was explored through analysis of a design database. These principles of prototype design and fabrication guide the embodiment process of a prototyping effort. The results of this research can be used to select between various prototyping techniques, implement them in a systematic strategy for the overall prototyping effort, and to guide the design and fabrication of each specific build. These contributions form a substantial basis for a methodological approach to prototyping which has not previously been available.

Chapter 2 Prototyping: State-of-the-art in Techniques, Methods, and Design Science

OPENING REMARKS

This chapter explores and reports on the body of prototyping literature. Significant experimental design research has been undertaken to quantify contextual and practice-based variables that are correlated with successful prototyping efforts. This chapter surveys design science, engineering, fabrication, manufacturing, additive manufacturing, rapid prototyping, and engineering education literature regarding: high-level objectives of prototyping, integration of prototyping in the design process, systematic methods to enhance the effectiveness of prototyping, and comparative review of fabrication technologies. Key examples of the relationship of prototyping and design outcome are: earlier prototyping, constructing prototypes with fewer (more integrated) components, and faster prototyping tend to correlate with high performance outcomes. Indexed overview tables are also provided in each section. These compact summaries of research findings are particularly intended to aid in comparing the potential benefits and costs of various techniques. An example is that parallel prototyping is commonly cited as a means for exploration, while iterative prototyping is cited for refinement. The chapter concludes with a summary of best practices, key points of potential risk, and a number of potential avenues for continuing innovation in the scientific research of prototyping for design.

2.1 INTRODUCTION

Different forms of prototyping are apparent throughout product and systems development efforts. The cost of developing a prototype is also often non-trivial in terms of person-hours and other resources. Implementation of a clear prototyping strategy can reduce ambiguity in expected objectives and benefits. Systematic prototyping can also enhance the probability of successful early product development. Significant effort has been made, by a variety of design science research groups, to explore and quantify prototyping practices that were historically considered purely intuitional.

This chapter presents a synthesized review of design science, engineering, fabrication, manufacturing, additive manufacturing, rapid prototyping, and engineering education literature relating to the topic of developing an informed prototyping process. There are five primary sections to this review:

1. Objectives and outcomes of prototyping
2. Incorporating prototyping in the design process
3. General principles for prototyping
4. Strategic techniques for prototyping
5. Comparison of fabrication technologies

The objective of this review is to explore theoretical and experimental (or empirical) research on identifying and understanding prototyping principles, critical process variables and types of prototyping, and associated correlations to design outcome. Section 1 reviews high-level objectives of prototyping. Section 2 outlines research on integrating prototyping with other aspects of the design process. Section 3 reviews the general theory of design principles, and specific principles for prototyping. Section 4 provides a detailed review of strategic methods. These methods help to enhance the repeatability of successful outcome, and increase the efficiency of resource deployment. Finally, Section 5 provides a comparative overview of fabrication techniques.

Building on this review, the work aims to identify critical areas of emerging research, and potential future directions for experimental studies of prototyping. The techniques and methods presented in this chapter also help to cross-compare the many forms of prototyping which are available. Figure 2.1 depicts several prototypes from research projects of the SUTD-MIT International Design Center (a joint venture of Singapore University of Technology and Design (SUTD) and Massachusetts Institute of Technology (MIT)) and one from an Instructable [24]. These examples include several different forms of prototype.

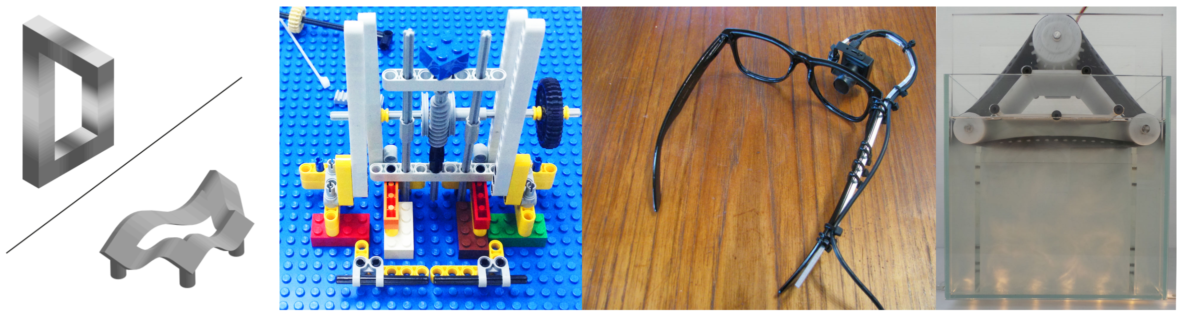


Figure 2.1: From left to right: CAD render of a prototype 'M.C. Escher' sculpture figure from two views; LEGO prototype for an atomic force microscope stage; functional prototype for a DIY eye-tracking design (adapted from ‘The eyewriter’ [24]); a functional fluid flow visualization chamber prototype. Each of these prototypes has a different level of fidelity, and was fabricated using different processes.

Setting the Stage

A physical prototype is a fabricated object that approximates a feature (or multiple features) of a product or system [19]. Prototypes convey and feel; they can also provide a venue for validating or improving hardware selection [19]. Design and prototyping have been interwoven throughout history. Michelangelo used physical prototypes to communicate construction details, and for marketing to investors [2]. Palladio used full-scale wooden prototypes of architectural elements to plan costly stone works [2]. Henry Ford explored nineteen models (some of which were prototypes) before finalizing the revolutionary model T design [3]. The triumph of Dyson's cyclonic vacuum was only achieved after 5,127 prototypes [4].

There are overall trends in how individual industries approach prototyping [25]. Some are driven by achieving specifications (typically those developing large and complex systems), while others, typically more agile firms, focus on prototyping to explore and develop a design [25]. There are several apparent context factors (risk, capabilities, requirements, etc.) that are critical to planning a prototyping effort [17].

Prototyping implies a certain partitioning of a design problem or opportunity. This partitioning influences the nature of information that can be explored and learned from a prototype[18]. Therefore, a prototyping strategy should carefully planned, with specific attributes related to the application [17]. Designers may explicitly consider what type of activities (testing) will be performed with the prototype, and assess associated risks [19]. Strategic methods include planning tables [10, 19], and heuristic guidelines [26-31]. Factorial experiments may also assist greatly in identifying critical parameters [19]. Despite the fact that prototypes may differ in some aspects from a final product, they provide a concrete interface between the designer (or user) and the design space [11]. It is critical to include consideration of how a design will affect human behavior. Prototypes permit the acquisition of this knowledge by direct interaction with customers and stake-holders (individuals and groups) [32].

Experimental studies have explored the engagement of prototyping in various activities. For example, concept generation is encouraged to evolve with and be informed by the prototyping process; proof-of-concept prototyping could occur throughout any phase of the design process [33]. It has also been observed that successful teams engage in more collaborative work, which physical and virtual prototypes can facilitate [34].

Research shows that using a taxonomy of prototypes may foster communication within multidisciplinary design teams [35]. Several detailed taxonomies of prototypes have been proposed. A typical first taxonomic division is between prototypes that address form and those that address function [19, 36, 37]. Another common distinction is the variable level of fidelity of a prototype with respect to the final model [8, 38]. Finally, a distinction is typically drawn between virtual (simulations, visualization or computational geometric modeling) and physical models [38]. This work develops an expanded index which provides a functional model of the expected outcomes of various prototyping activities through synthesis of empirical studies.

2.2 Objectives and Outcomes

There are many potential objectives to prototyping. This section explores a set of objectives and outcomes that have been explored in some detail across multiple sources. Figure 2.2 presents several of the most common objectives, where prevalence of the objective is proportional to box height in the diagram. The objectives where listed in each of the articles from this study which addressed this topic directly. For example, 29 articles from the review directly referred to refinement as a primary objective of prototyping. The binning was completed iteratively by comparing definitions. For instance, 'exploration' was binned with 'navigate the design space', as in both cases the same activity occurs. This prevalence is a rough metric that identifies where the literature appears to have the most focus relative to each objective. Although this analysis is independent of the value or potential impact of each objective, it helps to outline the literature's focus. This list of objectives builds on lists identified in other foundational works. Details are expanded throughout the section.

Figure 2.2: Frequently cited prototyping objectives. Each box's height is proportional to the number of sources from the review which refer to a given objective. Refinement, communication, and exploration are the most frequently observed.

Refinement

Several of the benefits of prototyping relate to design concept refinement. Prototyping is used to clarify requirements and reveal critical design concerns [12]. Physical models, or prototypes, help to identify potential changes in a design, and result in performance increase [39, 40]. Prototypes may also be tested under a variety of conditions [19]. These conditions may be binary or continuous [19]. A parametric prototype may be used to this end, in which styling and other design features are optimized via the sequential testing and manipulation of parameters [41]. Another refinement activity is simulated use [19].

The US Department of Defense (DoD) uses prototypes as a forum for competitive design, system demonstration, manufacture planning, cost estimation, and risk mitigation [42]. Some of the other benefits observed by the DoD are: quality decision making, early change incorporation, system interface testing, and earlier testing [17]. An observational study resulted in identification of several related benefits of prototyping including: feasibility testing, error reduction, and realistic requirement assessment (including correction of erroneous mental models) [6]. In tandem with these findings, the study identified common mistakes made in prototyping efforts which may include unexpected critical failure loads/modes, interface misalignment, and high cost [6]. It has been experimentally observed that physical prototypes are superior for identifying unexpected issues, and virtual prototypes are superior for refining function [38]. A relevant key difference between physical and virtual prototypes is that construction of a virtual prototype does not consume material. However, virtual prototypes do require a pre-established theoretical model of phenomena relevant to the design.

Communication and Usability

Research supports prototypes as essential in the exploration of usability [43]. Prototypes enable observation of interaction between the user and the device, or between multiple users (if it is relevant to the specific design) [44]. It is likely for this reason that developers frequently employ prototypes for the purpose of illustration [7]. Designers at IDEO (Palo Alto, CA), for example, list understanding experiences, exploring designs, and design concept communication as the core value generating activities for prototypes [45]. A meta-review of case studies reports that rapid prototyping was a success in 85% of cases, and with significant benefit for enhancing usability of a design, ease of use, and user needs identification [12]. Prototypes can also demonstrate the feel of a product, or provide an avenue for marketing [19]. From a meta-review of industry case studies on prototyping, it was found that rapid prototypes reduce designer effort, increase end-user participation, enhance cost estimation accuracy, and require less expertise to implement [12]. These effects may be due to the reciprocal relationship between requirements and prototypes; in other words prototyping clarifies requirements and leads to these outcomes [12]. An experimental study supports that deploying a rapid prototype during client interactions significantly enhanced quality and usability of the design, as well as promoting relations with the client [46].

Exploration and Validation

Two high level processes in design with which prototyping can be associated are divergence and convergence. Divergence implies gathering information and generating new concepts, while convergence implies selecting or refining one or more concepts [9]. In other words, two key roles of prototypes are exploration and validation [7, 8]. Some companies, particularly those working in highly complex systems, drive prototypes by specification as a metric for success, while others emphasize continual explorative prototyping [25]. Experimental data supports that a key goal of prototypes is to test and select among concepts [47]. Investigation of industry also shows that practicing designers frequently use physical prototypes to successfully aid in the concept generation process [48].

Active Learning

In this context, active learning applies not only in the educational sense, but in terms of advancing designers' mental models of phenomenal interactions. A study from psychology finds that when children are tasked with ordering physical objects before using them to explain a concept (such as division) their cognition is higher than if the objects were pre-arranged (for instance, set in ordered rows) [49]. Experimental analysis of prototyping also shows that use of prototypes is directly correlated with knowledge acquisition about the design space (this is in turn correlated with success) [50]. Another study of industry-academic design project collaborations, observes that physical models demonstrate flexibility across a range of disciplines and generally support design education [51]. Student's in design courses report that hands-on experiences increase the relevance of coursework [52-54]. Study of a cross-course machine shop prototyping project supports that prototyping facilitates hands-on learning and results in knowledge integration [55]. Finally, from ethnographic observation of practice, prototypes appear to be critical in the psychological experience of the designer, for re-evaluating failure as an opportunity to learn, enhancing a sense of progress, and encouraging creative abilities [56].

2.3: Prototyping and Design

A number of experimental studies have explored how and when to integrate prototyping into the design process. This subsection reviews several topics with regard to prototyping and the design process, while Subsections 2.4, 2.5, and 2.6 review prototyping design principles, strategic techniques, and fabrication, respectively.

Table 2.1 highlights a few points that will be examined.

Variable	**Design Heuristic**
Timing	early prototyping is the most critical
Ideation	prototypes lead to functional ideas
Fixation	fast prototyping reduces fixation
Feedback	feedback may induce corrections but also increase fixation
Parts	part integration is correlated to success
Fidelity	higher fidelity representations lead to accurate interpretation of the design
Usability	end-user testing (usability) may increase assessment accuracy

Table 2.1: Overview of general findings on prototyping in design. Detailed references supplied in the following section.

Timing

One of the essential and expected benefits of prototyping, as observed from a DoD study, is to act as an early-stage mitigation of risk [57]. It is critical that the process occur early for success [57]; and to prototype the most difficult components first [19]. From another DoD study, prototyping efforts occurred more often (20.5% of all projects) during the first phase than the second or third phase of prototype development (phases in this case simply refers to segmentation of the project timeline) [17]. However, a review of industry practices observes that the mean time to prototype from concept can vary greatly by the company. These differences may be driven by practical aspects of design context (such as system complexity) [25]. An industry informed method thus implies that designers need to explicitly and strategically consider when to engage in prototyping [19].

There are significant experimentally tested correlations with timing and prototyping [58]. A video protocol study of physical artifacts during design found that on average, in terms of physical interaction, tools were handled more often than sketches, notes, or the product itself [59]. Designers spend on average only a small percentage of actual design time handling a physical object. The majority of time is spent in learning and observing visual patterns (looking at the objects or sketches) [59]. Observation shows that successful teams start prototyping earlier in the process and do so throughout a project, while less successful teams used notes and a computer more often [34]. Late prototyping is correlated with unsuccessful efforts [34]. In fact, surprisingly, committing a larger amount of time to a project does not correlate with greater success; however, there is a strong positive correlation with early time spent prototyping (towards the beginning of the project) that generally decreases over time [58]. Specifically, prototyping during the first 30% of a design project is strongly correlated with success

[60]. A strategic prototyping method was shown to induce earlier and more frequent fabrication. This method resulted in a performance increase compared to a control group which was not exposed to this method [27, 29]. A related method, focused on aiding designers in selecting between virtual versus physical prototyping, also appears to encourage earlier prototyping. In this study, the final build was physical, and the participants chose between either physical or virtual modeling as the platform for concept development and iteration [30].

Ideation with Prototypes

Prototypes are critical not only for evaluation, but also for inquisitive exploration of concepts, as they enable organic learning and discovery [61]. However, it is important to strategically employ prototype-assisted ideation. For instance, Toyota developed a novel method of initiating all design in CAD, to remove the inaccuracies of traditional scanning of clay models. A general observation of this change was that the design team was able to explore changes much more rapidly with lower risk. There was also a smoother integration with manufacturing as the parts were already modeled [25]. A case study of design firms finds that practicing designers successfully incorporate prototypes into ideation [48].

Experimental studies have also made significant findings about prototyping and ideation. Ideation with prototypes can increase the percentage of functional ideas versus pure sketching, and a sufficiently simple (fast) method of prototyping will have equivalent novelty to pure sketching [39, 62]. In this context a functional idea was defined as a concept which is feasible to build and test with the given material restrictions. Another study found that individuals provided with foam core (a continuous material) instead of erector sets (a modular, discrete material) included dimensions in sketches [63]. Another study found that constant prototyping led to new design ideas as compared to late prototyping and no prototyping conditions [64]. Physical model construction may also help identify differences between a concept and real behavior [65]. Further study may be required to fully map the relationships between prototyping and ideation [59]. However, given the observation that prototypes lead to functional ideas [62], and a recent study that design concept quality is critical to outcome [60], the potential benefit of interweaving prototyping and ideation is clear.

A survey found that industrial design engineers, both graduate students and professionals, used objects and images for inspiration in design ideation more often than text [66]. Professionals typically report supporting CAD design with external sketches [67]. Representation form may also affect what type of design information can later be extracted [68]. A study shows that designers successfully and confidently extracted both requirement satisfaction, and functionality from physical prototypes (either low or high fidelity), and high fidelity (CAD) representations; while sketches permitted extraction of functionality but not requirement satisfaction [68].

Fixation Effects

An experimental study identified that introducing an exemplar to teams before prototyping began resulted in feature borrowing from that exemplar. However, teams not exposed to the exemplar borrowed features from each other instead. There was no significant difference in the total number quantity of borrowing [69]. In another study between a sketching only and a prototyping condition, where both were exposed to an exemplar, those given the physical prototyping condition were less fixated to the example [70]. The prototyping groups also produced designs with better performance, as would be expected from the previously reported correlation with low fixation and high performance [70]. One study found that prototypes may be used more often to communicate within domain analogies, and sketches for between-domain analogies. This case study was limited to a single team, however, and does not report full ideation results, only those related to analogy use [71]. A more detailed empirical study finds that prototypes will assist in mitigating fixation, but that a cumbersome prototyping process can slow down ideation to the point that variety will suffer. Empirical results show no reduction in variety with a sufficiently fast process compared to a sketching only condition [72].

Feedback on Prototypes

A case study observed that designers were hesitant to show prototypes to executives or managers, but they were comfortable showing their peers [25]. In some prototyping cultures, stakeholders expect high-fidelity prototypes, and may reject a project when presented with a low fidelity prototype [25]. A study of prototyping and funding at the DoD supports this conclusion with the comment that "*Admirals are inclined to sponsor huge money programs, not relatively inexpensive programs at 'a Captains budget*" [73]. Feedback can thus influence the way prototyping programs are designed in a reward cycle [73]. There is often an open question regarding 'who owns the prototype?' and design of the timing for engagement of management, customers, and suppliers, etc. should become engaged with the process [25]. An empirical study observed this tradeoff: feedback leads to corrected errors but may also increase fixation [64].

Novel Metrics

It is critical for designers to define the metrics that will be used to evaluate prototypes, and how the metrics may be assessed [19]. Considering one design field, there is a recognized problem in information science research that although meta-data is an important component of an information artifact, there is often little strategy for its assessment [74]. As prototyping is also often a form of information collection, it is critical to consider how the information gained from a prototype can be used more than once. In other words, prototypes are often designed, fabricated, tested, and discarded. There is an opportunity to develop means for integrating or tracking design knowledge across efforts.

Some methods place emphasis on metrics for usability. It is critical that prototypes capture the voice of the customer and the user experience during interaction [75]. A case-based study thus explored a novel metric for prototyping, which is the interactivity level [31]. An assessment table may be employed to evaluate the following aspects of prototype usability: context (use situation), function, inputs, tasks required of user, outputs, input-task-output cycle[31]. In this table, Likert values can be assigned to evaluate a prototype's interactivity [31].

Another set of metrics can assess the information fidelity in the representation. An experimental study compared the fidelity of several representations, as well as how confident the extractor is in the information [68]. This experimental study finds that higher fidelity representations lead to more accurate interpretations, and that prototypes are generally interpretable (compared to sketches) [68].

An experimental study observed a surprising inverse correlation with the number of parts and the success of a prototype [58]. In general, there is a nearly linear trend of part number increase over the course of project development [58]. However, projects that do not exhibit this trend are more successful; prototypes with more integrated components performed well [58]. This observation could potentially be applied in a feedforward approach. A designer could actively seek to reduce the number of parts in a prototype.

2.4: General Principles for Prototyping

Billy Koen observed that heuristics or principles are at the center of the design engineering methodology. They are characterized by provision of aid or direction towards the solution of a problem. They guide, but may not in and of themselves resolve a problem [21, 76]. Furthermore, a principle can be defined as an objective paired with a means of achieving that objective [77]. One avenue for basic design research is to categorize principle approaches in a given domain. Categorization and classification are essential to the development of design principles, as categorization facilitates the representation of large amounts of information in a compact form [22]. There are several established avenues for this type of research. Avenues include: critical analysis of design repositories, literature review and synthesis, controlled experiments, and deductive analysis. Several studies have explored principles of prototyping. Work in design research on *pattern language*, and content analysis also informs principle extraction [78, 79].

Five principles of do-it-yourself (DIY) prototyping were extracted from a study of the crowdsourced database Instructables.com. Instructables is a unique repository in that the over 100,000 entries contain not only representations of the final design, but also a cataloguing of the fabrication, failures, and process of development. Principles were extracted through iterative review of strategically selected entries in the database. Crowdsourced analysis was applied to validate presence of the principles. A controlled study was also conducted to determine that introduction of these principles to designers leads to enhanced prototyping outcome. This is compared to a control group that applied a traditional stage gate approach and was not exposed to the principles. These principles are [80]:

- *Hack commercial products* to reduce cost and effort of achieving function.
- *Employ basic crafting* to reduce the effort and cost of fabrication.
- *Prepare fabrication blueprints* to manage complexity and increase accuracy of fabrication.
- *Repeat fabrication processes* to increase the efficiency of fabrication.
- *Include structural voids* to increase strength to weight ratio of the prototype.

Prototyping principles were also extracted from the repository Thingiverse.com. Thingiverse is an extensive repository of three dimensional modeling files. It is primarily intended as forum to share source components for additive manufacture. One advantage of Thingiverse for design repository analysis is that design evolutions can be tracked through a function of the database called 'remixing' in which a parent (original) part is modified and reposted to the site. Principles were extracted by identifying changes between remixes. Twenty three principles for additive manufacturing design prototypes were identified from this study. Example principles include: reduce weight, material cost, and preserve stability by replacing solid volumes with cellular structures; minimize design time and effort by reusing already-designed component geometry; minimize assembly time and number of components by incorporating snap fits when possible [81]. It is notable that several prototyping principles were common to both of these studies.

In a general way, this literature review also leads to the identification of prototyping principles. Observations from the objectives section can be paired with individual techniques to achieve principle approaches. This comparison is highlighted in Table 2.2, which follows in Subsection 2.5.

2.5: Individual Techniques

An individual technique is a process for resolving one aspect of a prototyping effort. Techniques guide development more directly than a principle. However, the choice of whether or not to implement a given technique must be weighed carefully. They can be integrated in strategic methods for the prototyping process [26, 27, 29, 82] . Table 2.2.2 provides a general mapping between objectives and techniques. The content summarizes results from the empirical research. Expected benefits and challenges of individual techniques are listed according to frequency of citation. If there were several empirical sources that identified an outcome, then it would map to the frequently cited bin. This chart helps to identify objectives of each individual method at a glance. It functions as an index. The rest of this Subsection expands details of each technique.

Legend (how frequently each outcome is cited as a likely outcome of a technique):
● - frequently cited
◑ - occasionally cited
○ - rarely cited

Individual Techniques	Outcomes: Refinement	Validation	Exploration	Communication	Active Learning	Usability	Reduce cost	Reduce time
Requirement Relaxation	◑	●	◑	◑	◑	◑	◑	◑
Mockup	○	○	●	●	●	●	●	●
Isolated Subsystem	●	◑	◑	○	◑	◑	●	●
Scaled Prototype	●	◑	●	●	◑	○	●	◑
Iterative Prototyping	●	●	○	○	●	○	◑	○
Parallel Prototyping	○	●	●	◑	●	◑	○	○
Competitive Prototyping	◑	●	●	◑	○	◑	◑	◑
Cooperative Prototyping	◑	◑	●	●	●	●	◑	◑
Virtual Prototype	●	●	◑	●	◑	○	●	○
Mixed Prototype	●	●	◑	●	●	●	◑	○
Physical (complete)	●	●	○	◑	◑	◑	○	○

Table 2.2: Mapping between techniques and likely outcomes. Relative frequency with which each outcome is cited as an expected benefit of each technique.

Relaxed Requirement Prototyping

For some prototypes, the requirements may be relaxed from final values (example shown in Figure 2.3). Motivation for this approach can be explained by the tradeoff between model accuracy and cost [19]. A less accurate model may at times be sufficient because of the benefit of reduced costs. DoD research identifies that a low fidelity prototype (or a “strawman”) is essential for early stage risk reduction and refining design requirements [17, 42, 57]. Early stage low fidelity prototyping can facilitate “moving the ball forward” [83]. Relaxation of requirements must be implemented carefully to ensure that useful information is obtained. It is critical that the prototype is tested in a realistic environment [42]. The designer can specify what requirement simplifications are acceptable for a prototype [19]. It has been suggested that threshold minimum requirements can be addressed in early development stages [84]. Relaxed requirement prototyping can act as a facilitator to parallel prototyping and iteration [85] at a more rapid pace [42]. This can also be achieved without loss of function. An example is retrofitting new function to an existing product (reduced fabrication requirements) [86]. With this approach, however, it is critical to realistically assess feasibility and cost of manufacture [87].

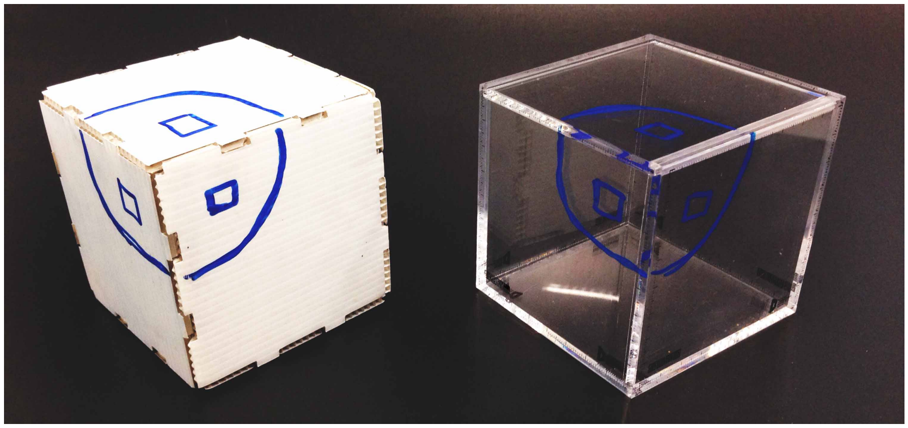


Figure 2.3: Example relaxed requirement prototype (left) and full fidelity requirement prototype(right). The design is a whiteboard cube. The relaxed requirement prototype is made from poster board. It allows examination of feel and function at low cost, but durability is very low. The acrylic pre-production prototype on the right is fully functional. The cost and time of production were substantially higher for the full prototype. It was only produced after the relaxed requirement prototype was tested successfully.

Experimental studies have explored prototype requirement specification. Prototype fidelity predetermines potential for certain insights from a prototype [68]. In general, the order of decreasing fidelity is given by: high fidelity prototype, low fidelity prototype, CAD, sketch [68]. The first three may permit successful functional interpretation; however, only high fidelity prototypes are observed to permit assessment of full manufacturability [68]. Low fidelity prototyping fosters a sense of forward progress, learning from failure, and concept expression without fixation on detail [88]. Methods have been demonstrated to guide successful implementation of requirement relaxation. A strategy method has been shown to induce requirement relaxation at early stages to improve design. It was also observed that relaxed requirement prototypes cost less and required less time to build [26-28]. The strategic relaxation of requirements on early prototypes does not seem to have any adverse effects on final performance [29].

Mockup Testing

A mockup is a prototype that demonstrates a feature(s) of a system or product concept in an abstract, high-level way (example shown in Figure 2.4). Although mockups may only approximate a system's or product's actual physical behavior, they are very useful and may be more practical in some stages of development [19]. Techniques in this category (storytelling, vignettes, cartoons, and amateur videos) can also be more holistic and touch on several points at once [89]. They can also incorporate the designer's play acting usage scenarios (and components) by the designer, such as IDEO's bodystorming [45]. Scenario methods can be enhanced with preconceived action prompts to guide scenarios, or with requirements for quantitative observation such as note taking at timed intervals [45].

Figure 2.4: Illustration of an actual paper mockup for the structure of an atomic force microscope casing. The model was fabricated (with paper and clay) in less than 15 minutes.

Recent studies have identified that scenarios can be explored through narrative to achieve novel predictive modeling results. An applied narrative for the purpose of exploring a functional design is known as Zygotics, or science fiction prototypes [90]. The designer constructs a narrative to introduce the design into various potential future scenarios [90]. This method enables an immersive experience of the design that might be otherwise impossible [91], as well as encouraging precognitive analysis of the design's interaction with people and circumstances to make new discoveries [90]. It is effectively cognition-based usability testing. The following is a sample taken from a Zygotic Vignette [90]:

> …Freeway Savage was the first in his downtown zonal grid to install the device. As he walked to the bathroom he heard the letterbox yap and a delivery thud onto the floor. Curious, he entered the hallway and picked up the parcel with its FedBot logo. He wasn't expecting a delivery, but then it wasn't about expectation these days. Weighing the package in his hands, Savage moved back into the bedroom and sat heavily on the bed. The box contained a power cell, a replacement for the Living Wall^{TM} energy port which was, he now understood, about to run out of juice.
>
> …Smith held up a finger to indicate a question: "This ADEM App. It predicts when the people it serves need things, yes?"Servis' mood picked up. "Take a pair of sneakers, Chief. The Trypolysinuate sole has built-in sensors which enable it to monitor its own state of depletion. It's constantly feeding this data back to the Cloak. And it's the same for every other product in the citizen's life.

Mockups can also represent a partitioned effort. For instance paper mockups could represent the functionality of different subsystems of a design [92], e.g. software and hardware are each represented with distinct mockups [92]. Paper mockups were found to be roughly equivalent to virtual prototypes for obtaining usability feedback in a software interface design experiment [93]. Mockups may be particularly useful when capabilities do not permit fabrication of a functional form, or if modifications are desired from non-experts [93]. An experimental study, of website menu design found that paper prototyping encouraged meta-discussion of the grouping of menu topics [94]. This may be because low fidelity prototypes encourage high level discussion, as only the basic concept is present [95].

Isolated Subsystem Testing

In isolated subsystem testing, a prototype is segmented, and a single subsystem (or group of subsystems) is explored in isolation (example shown in Figure 2.5). Constructing subsystems in isolation can permit development of a tailored strategy for that subsystem [84]. A study of military design efforts found that isolated subsystem testing (for large and complex systems) can provide useful data for about 60% of the cost of an integrated prototype [42]. Specifically, each subsystem can have a unique set of requirements [15]. The subsytem prototypes may be a mixture of physical, virtual [15], or even a scaled model [96]. Isolated subsystem prototypes can also aid in ideation with users [97].

Figure 2.5: An example isolated subsytem prototype. This is a testing rig for a three-phase mechanical pitch sensor on a rolling cart robot. The system is completely isolated. Electrical contacts are not included. The only function being tested is the relationship between tilt angle and the position of the rolling contacts. The basic phenomena of the sensor geometry can be evaluated without time expenditure on the wiring or other systems.

It is possible to pseudo-connect the isolated models (see also mixed prototype). This approach is analogous to designing the elements of a network. In this network analogy, it is critical to simulate information transmission across interfaces. Artificial interfacing also permits design of control system design without an integrated prototype. A case study demonstrated an artificially interfaced model for subcomponents in a vehicle chassis that achieved 95% test accuracy to the integrated chassis model on average (90% minimum accuracy across varied test conditions) [15].

Isolated subsystems can be used as a mechanism for generative design. For the example in Figure 2.6, and other cases of tectonic design, the designer specifies properties of a basic building block. Then an algorithm works to construct a more complex figure, using these blocks. This approach has been demonstrated at the research level. However there are currently only a few commercial applications supporting tectonic design [2].

Figure 2.6: A tectonic artifact adapted from [2]. Although the super structure is complex, the form was segmented into simple-to-manufacture triangles with an algorithm.

Experimental studies have explored isolated subsystem testing. Presenting each function of the design with a separate abstract representation enables rapid in-depth exploration of different types of information [97]. A strategy based method can encourage use of subsystem isolation [28]. Isolating a subsystem significantly reduces the cost of prototyping without adversely affecting performance [29]. However, it may be more difficult for isolated subsystems to address unanticipated needs [98].

Scaled Prototyping

A scaled prototype mimics behavior(s) of a larger (or smaller) design through similitude (example shown in Figure 2.7). The discovery of similitude is attributed to William Froude, in the 1870's [99]. Froude discovered that by identifying critical factors of a phenomenon (e.g. the way gravity drives wave formation), one can develop the models to extrapolate real conditions from scaled models [99]. By the 1940's this technique was fully integrated into US naval design programs [99]. Scaling may enable prototyping in cases where a full scale model is not feasible [84]. Therefore, scaling can also be used to save resources [19]. As the economy of computer models increases, it becomes possible to scale virtual models to include incredibly dense design information [100]. While certain buildings were once represented as a series of basic blocks, they can now be organically crafted in each detail [100].

Figure 2.7: Example of a scaled prototype. In this case an architectural design can be examined in detail for very low cost relative to a full scale model.

Empirical similitude is an advanced technique of similitude; it is based on forming the vector product of multiple models of similitude (which are each similar in a different variable) for the final design [101-111]. There are a number of alternative mathematical techniques for approximating the vector product and generating models, where the accuracy is typically high for such domains as heat transfer, mechanics and non-linear fluid dynamics [101-111].

Use of similitude scaling can be induced with a strategy method. A controlled empirical study with participants from mechanical engineering found that scaled models cost significantly less than full prototypes without adverse performance effects [26, 28, 29].

Iterative Prototyping

Iteration is the sequential testing and refinement of a prototype [84] (example shown in Figure 2.8). It is reported as a key strategy element, and allows gradual achievement of requirements [84]. Iteration is particularly useful to meet rigid (challenging) requirements [10]. Iteration is critical to obtaining insights into difficult issues, managing high uncertainty, identifying errors and simplifying parts [112]. Regarding iterations to increase modeling accuracy, a probabilistic approach was used to estimate that a prototype will have sufficiently little error after a number of iterations proportional to the ratio of avoidable cost (of malfunction) divided by the testing cost [85].

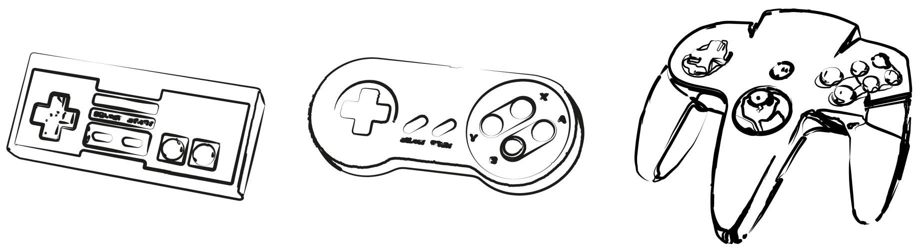


Figure 2.8: An example of iterative design. These three controllers show vast improvements in ergonomics with each iteration.

Iteration can be used to improve a design concept. Several controlled experiments have shown that groups iterating on a design significantly outperform teams without iteration, based on the evaluation of self-efficacy and design requirement satisfaction [26-29, 113]. It has also been shown that a strategy method can induce the use of iteration, compared to a control group [27]. Further exploration has shown that there is a continued and marginal benefit to iteration of approximately 12% performance increase per build for the cases studied [29]. This increase continued even up to 20 iterations at the end of a study [29]. There also appears to be a reduction in time required to execute iterations. One study showed a 75% drop between the first and second model, and an 8% average drop for continuing iterations [29]. However, an observational study noticed that selection of fabrication methods has a significant impact on how many iterations are pursued on average (a more complicated method leads to fewer iterations) [114].

Parallel Prototyping

In parallel prototyping, multiple potential design concepts are fabricated and compared in parallel or concurrently (example shown in Figure 2.9). Parallel prototyping can help provide critical feedback for concept selection [84]. A prototyping effort may also explore an opportunity or problem through subdivisions in parallel [18]. Designers at IDEO are strongly encouraged to bring a prototype, or several, to each meeting [83]. A probabilistic study suggests that to maximize profit, the number of parallel designs can be proportional to the ratio of profit uncertainty to the cost of each design [115]. Or, in a more general way, multiple designs in parallel are encouraged when cost (budget) is flexible [10].

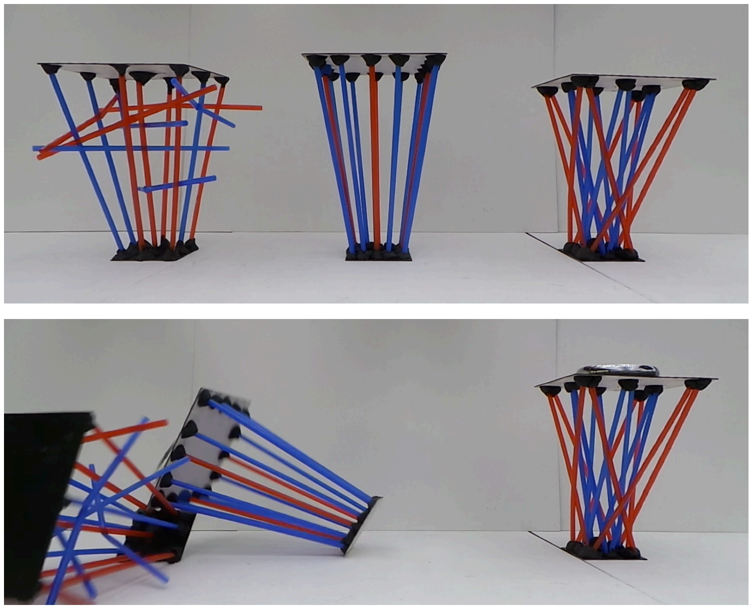


Figure 2.9: An example of parallel prototyping. Three alternative proof of concept designs for the strut distribution in a prosthetic leg are explored simultaneously. *Top* three designs before testing. *Bottom* after a metal weight is placed on each prototype.

Experimental studies support the benefits of parallel prototyping. Several controlled experimental studies have shown that groups producing prototypes in parallel produce designs that significantly outperform groups producing a single design [29, 116-119]. This result holds true whether the teams are iterating [116, 117], or only executing a single test [119]. Participants in an empirical study who pursued parallel prototyping reported an increased sense of time constraint as compared to teams that only prototyped a single concept [119]. Pursuit of parallel prototypes may lead to higher concept diversity [117]. Presentation of several prototypes during critique can result in higher quality. Multiple prototypes permitted comparative evaluation of features, as opposed to purely negative/positive evaluation [118]. A strategy method has also been shown to encourage utilization of parallel prototyping compared to a control group [26].

Competitive Prototyping

Competitive prototyping implies parallel prototyping engaged by separate entities (example shown in Figure 2.10). Competitive prototyping was developed at the Department of Defense to decrease expenditure [120]. However, competitive prototyping is effective in shorter term challenge activities between design teams (even with 3-5 individuals per team). The benefit of having separate entities is that it allows for high design divergence [120]. Having multiple teams working on the problem can improve outcome [5]. In cases where contractors are competing, it allows comparison of alternate designs before committing to production [121]. Competitive prototyping also increases awareness of latent design requirements and aids in quantifying feasibility [73]. The physical embodiment of competitive designs is even more critical for large scale projects due to high risk factors [120]. Although it may increase cost to explore competing prototypes, the overall design costs likely will be reduced [121]. One risk is that the information produced by each effort may not be integrated. Knowledge integration is critical [122].

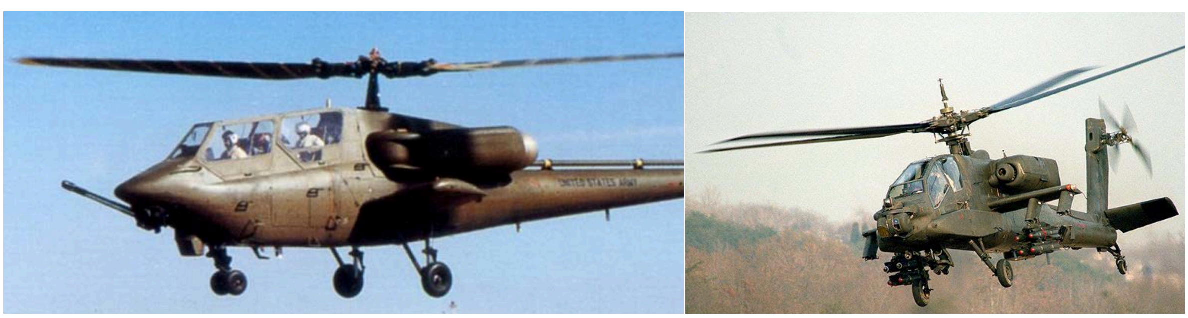


Figure 2.10: An example of competitively produced prototypes, adapted from [120]. These two helicopters were competing prototypes for a DoD contract. This approach allows for tangible comparison.

Cooperative Prototyping

In cooperative prototyping, a group of users and designers are actively engaged with each other during concept development [123] (example shown in Figure 2.11). The system or product under examination may even be under control by a designer/operator in a separate room [123] (an augmented prototype), or simply a demonstrative mockup [124]. This tangibility makes the user's feedback concrete [124]. In cooperative prototyping, the physical model is a catalyst for discussion about actual usage; therefore, it is critical that interaction (that the user has with the prototype) is open-ended, rather than proscribed by the designer [125]. An experimental study shows that providing multiple designs for group feedback in a cooperative setting produced a better outcome, compared to providing only a single design [118].

Figure 2.11: An example of cooperative prototyping. In this case, the designer is discussing design requirements with potential users who have prototyped and presented a mockup of the product.

Virtual Prototyping

A virtual prototype is one which is developed (and tested) on a computational platform (example shown in Figure 2.12). A review of the prototyping literature identifies that virtual models can permit complex analyses and facilitate production [84]. However, physical models provide unique user interaction capabilities [84]. Virtual models may also leave out unexpected phenomena [19]. However, the advancement of computer-aided design and computational technology has enabled models that are both physically large and contain detailed design information [100]. These constructions may both be aesthetically graceful and accommodate diverse functionality [100]. Virtual models also allow for coupled design of the components and the manufacturing process [126]. Virtual designs also present new possibilities. Simulation, e.g. a product demo, can be held concurrently in many locations [14]. Virtual prototypes enable perturbation studies on design features at rapid pace and reduced cost compared to physical tests [84].

Figure 2.12: An example virtual model. This CAD chair model, adapted from L. Sass [127], can be viewed and modified without the need for costly fabrication.

Virtual models allow for novel approaches to data collection. An example of this is taken from design of a rocket test chamber simulation at NASA. Test data was collected from a rocket in a chamber. The chamber and rocket were modeled in one simulation, and refined until the simulation matched experimental data. Then the chamber was removed in the simulation. This way, an accurate model of open-air performance was developed [128]. At BMW, a detailed wheel model provided low cost data that is considered to be as accurate as that from track tests [128]. This test also provided measurements which would be physically impossible to sense and record with a physical test [128]. For example, a virtual model can reveal key frequencies or loads that cause fatigue, which a physical test could not easily show [129]. Virtual product models, for example, sportswear, can be parametrically refined with virtual custom user models [130]. Models of a scoliotic correction-brace can simulate patient response with lower risk [131]. Virtual models can be supplied with multiple user data, such as for ergonomic exercise equipment [132]. Larger logistical problems can also be incorporated, for example, the entire process of constructing a bridge, including vehicle paths, platform design, and materials supply channels to avoid potential collisions, rebuild errors, and for resource optimization [133].

Virtual modeling can also be used as tool to automate some aspects of design. Certain classes of problems that lend themselves to functional synthesis can be decomposed to grammatical formalisms, allowing for algorithmic generation and evaluation of virtual models of design solutions [134, 135]. Computational algorithms can also support multi-component heuristics [136]. For example, a genetic architectural design algorithm might test both aesthetic and structural features of a generated model [136]. Virtual models can even include multiple agents [137]. An architectural design included AI user-agents that walk around and interact with features of the design [137].

Another example is rapid iterative design concept generation for geometry of a bus stop with passive air flow acceleration, as evaluated by computational fluid dynamics simulations [138].

Software design has reduced the effort of generating virtual models. Some developments in virtual modeling software include wireframe editable models to depict function [139], sketch-to-component automated recognition [140, 141], sketch-to-3D model recognition [142], or capture of 3D hand motion to draw 3D representations [143].

There are a plethora of impactful design problems relevant to virtual prototyping. Other novel virtual design cases include: custom prosthesis socket refinement [144], risk assessment and communication in construction of buildings [145], simulation of clothing that includes material drape [146], algorithmic design of automobile headlamp geometry and control circuit [147], or a virtual chassis manufacturing assembly environment [148].

The empirical research supports the utility of virtual models. Practicing designers report predominant use of CAD for documentation, sketches for mnemonics, and both for communication and ideation [67]. Virtual prototypes have drastically lower costs than physical prototypes with roughly equal performance [29]. A computer prototype was reported to require less effort, and perform as well as a paper prototype for usability testing [93]. CAD models also compared equally well to traditional hand-carved foam models in a design exercise [149]. Indeed, virtual prototypes were found to be the faster and higher performing alternative to cardboard-physical prototyping for a linkage design task [30]. In a trial project, students even successfully remotely designed a prototype in CAD, which was then 3D printed and tested [150]. For evaluation of a product, virtual testing was found to match well with physical evaluation [151]. However, tactile material properties (such as texture) are not perceptible in the virtual format [151]. Participants in a study reported that virtual models require less “unnecessary work” [93].

There are, however, a number of substantial limitations to virtual models. Virtual modeling requires a significant allocation of time to tool selection and perspective alignment [149]. This approach may take relatively longer, in some cases, than a physical prototype [29]. It is therefore critical to specify which parameters the model will address, to reduce unnecessary costs [152]. The decision to employ modeling versus physical prototyping can be driven by cost and expected accuracy [19, 153]. The approach with a higher ratio of accuracy to cost may be pursued [19, 153]. Virtual models may not capture all relevant physics [154]. However, advances in non-linear and multi-physics computational modeling capabilities are closing this gap [155].

Mixed Prototyping

Prototypes can be developed by integrating various physical and virtual elements in one model. There are several reported forms of this mixed approach.

One form of mixed prototype is the augmented reality prototype, in which auditory-visual simulations are overlaid on physical elements (example shown in Figure 2.13). Functionality is added to visible features by an invisible agent, in a manner like the "Wizard of Oz" [123]. The prototype can be virtual, physical or mixed, and the user can be real or virtual [156]. This permits critical usability assessment [123]. There are several basic forms of augmented reality: screens embedded in the device, vision augmentation, and projection [157]. In the projection form, certain functions are demonstrated by projecting video of simulated features onto a physical mockup [158]. This process can be enabled by tracking user motion [159]. Another augmentation might consist of a casing with display and buttons which simulate a camera that is actually tethered to a PC which handles the image processing [45].

Augmented reality facilitates capturing the voice of the customer in a uniquely quantitative fashion [75]. An augmented reality prototype might, for example, integrate eye tracking for detailed use assessment [156]. Cost and time are also saved [160]. Mixed prototyping facilitates the potential to engage more senses in the user interaction environment at an earlier stage (sight, sound, touch, etc.) [43]. A unique benefit is the ability to independently manipulate each sensory feedback [160]. A controlled study found an augmented reality prototype to provide the same usability data, from participants, as a physical prototype [161].

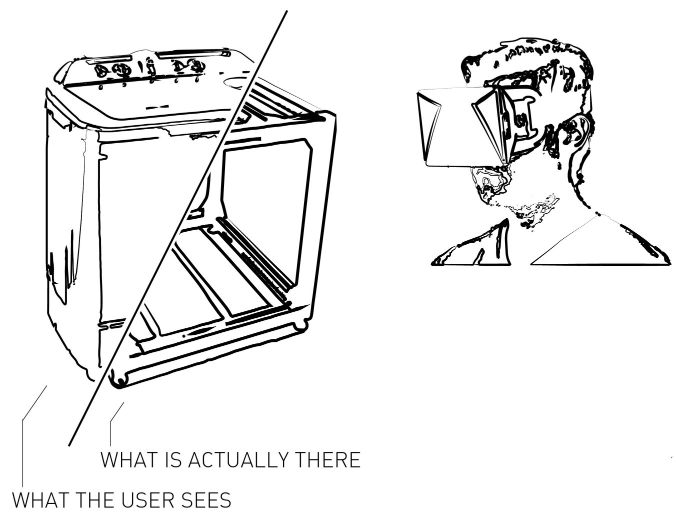


Figure 2.13: An example of a mixed prototype. Although in the physical world, there is only an aluminum frame; the users vision (and hearing) is augmented with a VR display to perceive a complete product.

There are many other examples of augmented reality facilitating design: an environment in which the user can modify a live-functional simulation [162], support for training in manufacture to enhance efficiency [163], parametric manipulation of a physical mockup that is captured and used to update a CAD model [41], VR goggles that are used to add detailed material depictions that are inserted to the user's vision (in this case objects were tracked with QR codes)[43].

Hardware in the loop simulations allow integration of both virtual and physical prototypes for simulation of a complex system [15]. This approach allows requirements specific to the particular subsystem [15]. Information can be transmitted between each subsystem as required [15]. Physical components are typically used for subsystems with high predictive error; such models may be scaled [96]. User-interaction is also possible [164]. For example, signals from a driver holding a physical wheel could be transmitted to a suspension model, which supplies feedback to a servo on the wheel shaft [164]. Image and motion capture systems can be integrated to obtain highly detailed information of usage [165].

A related, enabling, technology is haptics. Haptics provide tactile feedback to simulate forces supplied in the actual product [166]. An empirical study reported that adding haptic feedback to a mixed prototype was preferable to users [159]. One advantage of prototyping with haptic interfaces is in designing for visually impaired users [167]. Haptics can be classified based on what type of forces are applied (along different axes, rotating versus linear etc.) [166]. Haptics can also be used as a design tool; that is forces from a virtual model can be supplied as the designer interacts with it via a haptic interface [159]. A design trial reported that although the simulation of touch is crude, adding an element such as a ‘hammered surface’ was easier to apply and feel than with a physical model [159].

Methods can help in selecting what type of virtual or mixed model to pursue. Filippi has proposed a method to enable selection of a physical, virtual, or augmented reality prototype by prompting the designer to assign weights in a table of factors [168]. These factors include: realism, error recognition, functionality, and others [168].

2.6: FABRICATION

Various fabrication methods can be employed to embody a prototype. This section presents a detailed review of experimental research into novel fabrication approaches. Comparative research of the expected benefits of these methods is also reviewed. Table 2.3 provides a high level index of the approaches that are reviewed in this section. The table cross references approaches with expected capabilities. The approaches are general; for instance there are multiple subtractive methods. It is important to note that many other fabrication approaches exist. Other examples include molding or casting. The three categories were selected based on their frequent citation in the prototyping literature. The table was formed by evaluating the relative frequency with which each capability is cited. The 'frequently cited' bin is assigned when at least several articles refer to a given capability of a certain approach. Details are given below.

Legend (how frequently each outcome is cited as a likely outcome of a technique):
● - frequently cited
◑ - occasionally cited
○ - rarely cited

Approach			Capabilities: Low fixed investment	Low cost parts	Functional parts	Easy fabrication	Large quantities	Complex designs
COTS			●	●	◑	◑	◑	◑
Custom	Outsource		●	○	●	●	●	◑
Custom	In house	Handcraft	●	●	○	●	○	○
Custom	In house	Subtractive	○	●	●	◑	◑	●
Custom	In house	Additive	○	◑	◑	○	○	●

Table 2.3: General comparison of fabrication approaches. Relative frequency of various capabilities of each approach.

Component Source Selection

When prototyping, there are several options for component sourcing: in-house production, outsourcing, and commercial off-the-shelf (COTS) component purchase. COTS components, or catalogue ordered components, can often save cost and time [19]. NASA has used COTS for a proof of concept satellite system prototype [169]. Modular COTS parts systems can be used to generate arbitrary geometries. An algorithm has been demonstrated to generate segmented 'puzzle pieces' that interlock to compose a 3D form supplied from CAD. The method has been demonstrated with LEGO pieces [170].

For custom part design, two options are outsourcing or in house fabrication. Outsourcing permits pre-settled cost, and potentially enhanced quality [171]. Although outsourcing may be more costly it may reduce in-house strain, and provide access to specialized processes [84]. A Honk Kong ethnographic industry study finds that the decision to outsource or manufacture should consider organizational flexibility, expertise, and cost [172]. Technical facilities are another factor to consider, in-house manufacture may have unexpected costs (e.g. software, depreciation, material excess) [171]. Outsourcing a custom build may be avoided if the item or its manufacture is proprietary [171]. It is also important to note that when employing external contractors, reward structure may play a significant role in outcome [73].

Handcrafting

A rudimentary handcrafted prototype can be achieved with very little fabrication time (often on the order of minutes) [27, 173], whereas currently the fastest freeform fabrication process takes more than an hour for anything other than very small parts [174-176]. Handcrafting has a connotation of basic materials and fabrication methods [177]; however, the emergence of maker technologies (e.g. Arduino) enable handcrafting of advanced electromechanical prototypes [63]. It is also possible to generate fabrication patterns for handcrafting with computation [177]. Handcrafting also enables use of mixed materials and localized sourcing. In professional architecture, handcrafted models are traditionally used in several design stages. These range from feasibility models made in a single day, to full scale models that require four weeks of full time fabrication for final project displays [176]. Empirical studies show that handcrafting with continuous material (e.g. foam core) rather than modular materials (e.g. erector set) led to inclusion of dimensions in design sketches [63].

There is an emerging trend of individuals pushing forward the practice of micro-production from their own home [178]. This so-called DIY movement is a re-emergence of the craft tradition [166] that is enabled by low cost modular technology (like microcontrollers [179]) and the information infrastructure of the Internet [178]. Examples of enabling infrastructure are crowdsourced databases like Instructables.com, an offshoot project of MIT's Media Lab, which contains hundreds of thousands of detailed walk-through instructions for product fabrication (at home) for low cost and often with basic tools [24]. Example products found on Instructables include: plasma phase pulse speakers, bicycle to motorcycle conversion, or homemade video arcades. Another example is Thingiverse.com, which is an open source platform for sharing part files for additive manufacture [180].

Subtractive Fabrication

There are several methods for subtractive fabrication. These include blade cutting, ablative laser cutting, milling, and jet cutting technologies. Most operate within a fixed cutting bed, while it is also possible that material is fed in one direction past a rastering head (allowing for a flexible work size) [2].

Ablative laser cutting consists of rastering a high power laser over a 2D material [2]. Laser cutting often requires very little training and can be applied to a wide variety of materials rapidly [2]. Laser cutting is generally limited to planar cutting, however, some multi-axis laser cutting tools are under development.

Computer numerical controlled (CNC) machining is a subtractive rapid prototyping method [181]. Although the machine is costly and operation requires significant technical expertise (path debugging, etc.), parts are highly functional (for example made from cast aluminum) and rapidly produced [181]. CNC milling is restricted to line of sight cutting (no hollow parts) [182]. CNC-machined parts might be incorporated with parts from other methods for more flexibility [2, 183]. Another advantage of CNC parts is that they can be modified [184].

Water jet cutting is another form of CNC in which extremely high pressure water with a garnet powder suspension is used to supply the cutting force [185]. Water jet cutting can be extremely fast (300mm/min feed-rate); however, the feed-rate slows as material thickness increases [185]. The cost of water jet cutting a part can be as low as a few dollars, though the machine cost is roughly $25,000.00 USD [185]. It is possible to cut a great variety of materials with water jet cutting, from glass to stainless steel.

It is intrinsically obvious that planar subtraction can result in 2D parts. However, novel research has shown that it is also possible to produce arbitrary 3D forms with planar processing, i.e., sheet material (example shown in Figure 2.14). Typically this is achieved through a three step process: (1) algorithmic deconstruction of a digital 3D form, (2) planar plate fabrication, and (3) plate assembly [186]. This interconnecting array of 2D plates most often employs sliding friction joints [187]; however joints formed with another process can also be incorporated [2, 188].

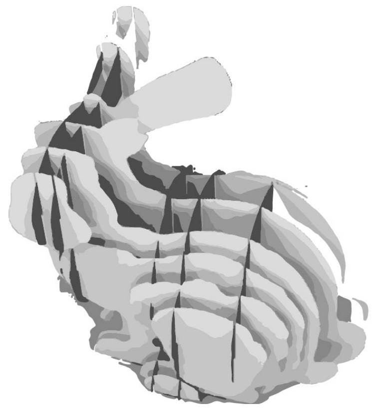


Figure 2.14: An example of a 2D to 3D form, produced by planar segmentation algorithm. Adapted from [189]

Various shape grammar segmentation algorithms have been proposed [187]. One demonstrates decomposition with ribs that are perpendicular to the compound surface [187]. It is possible to produce interlocking forms that either collapse in plane [190] or remain rigid (due to joint alignment) [191]. Multi-planar decomposition can enhance rigidity [192]. One algorithm even generates ‘pop-up’ forms from paper [193].

Several materials [194], and joining methods [127, 186, 195] have also been explored using this approach. Cardboard, paper and plywood can present incredibly low cost options for producing 3D artifacts [190-192, 196]. Use of plywood even permits functional furniture production [197, 198]. One algorithm reformulates approximations of existing 3D furniture from model decomposition. These reformulations have the advantage of not requiring additional fasteners [199]. Production of custom clothing has also been demonstrated (although sewing was required at the interface) [130].

Additive Manufacturing

Additive manufacturing (AM), typically refers to an automated sequential fabrication process which consist of the production of many 2D layers to gradually form a 3D part. Blanther can be credited with the inspiration for AM, who filed a patent for a technique of layered topographical maps in 1892 [19]. AM prototypes have many general applications: visualization, ergonomics, functional testing, manufacturing testing, molds, cost analysis, or marketing [19]. AM may even permit a direct transition between prototyping and manufacture. The range of specific applications for AM technology is vast, from 3D printed chocolate [200], to implants for facial reconstruction [201], or tile production for tectonic buildings [202]. A study finds that AM has a positive impact on design learning [203]. However, the utility of AM technology varies by application [176]. A realistic product can be produced in a short time period. This enables rapid iteration and application to highly customized situations (such as implants). However, some processes require multiple processing steps [35]. Implications of AM include: a more continuous design process (from concept to analysis); reduction of intractable problems (like doubly curved surfaces) [2]; exploration of many physical designs in parallel; and digitally composite materials. However, current CAD software has a limited capacity to fully engage some of these potentials [2, 188, 204]. As AM processes have several practical and theoretical layers of abstraction, and there are currently many opportunities for exploration and integration [205].

A number of design concerns have emerged relating to AM. Rosen proposes the question "Now that we can put material anywhere, how do we go about designing for that and why?" [189, 206-213]. This has led to the exploration and refinement of various finite element design algorithms for producing optimized meso-structures from a variable base cell design (variations typically include removal or thickening/thinning of struts in a lattice cell) to refine local quality [189, 206-213]. The file types used for maintaining and editing forms (STL is most common) also have various limitations [214]. Part slicing and orientation can drastically alter quality in many of the processes [215]. Algorithms have been proposed to: refine slicing algorithms [216], locally refine layer thickness

[216-219], refine printing paths [220], segment large parts for printing [221], or optimally re-orient parts [215]. Note that tolerancing may vary by process and result in negative or positive offset, depending on the nature of the process [220].

There are some observed limitations to AM. Currently, CAD modeling of functionally graded materials appears limited to experimental software [222, 223]. A case study demonstrates that AM was less affordable than small run ABS injection molding when several hundred copies of a small part (for a chain mechanism) were required [224]. Another case study also finds that interface assessment with AM parts may be inaccurate, although their production time is less than ABS injection molding [225]. Most current print beds are relatively small (less than 20 inches to a side), and there are various factors to be weighed when selecting among the various methods. A quantitative selection process may assist to consider cost, time, accuracy, material type, part size and part strength of each method [19].

Table 2.4 reports some average capabilities of commonly discussed AM technologies. This information is averaged from several reports [174-176, 182, 226-228]. Cost for several machines was updated from a manufacturer's website [229]. For some machines the cost has dropped by more than 98% in about ten years. These methods are reviewed in some detail in the remainder of the section.

	FDM	SLA	Polyjet	SLS	3D Print	LOM
Minimum layer thickness (mm)	0.15	0.10	0.15	0.20	0.20	0.15
Build rate (mm^3 per hour)	100	65	40	65	400	400
Build cost ($ per 110X110X110mm cube)	386	1230	2735	1170	125	220
Print volume, (average measure by in^3)	5000	7000	700	3000	2500	8000
Max part failure strength (MPA)	50	75	N/A	512.7	5	N/A
Machine cost, low end (USD)	200	2000	20000	50000	15000	22000

Table 2.4: A comparison of common AM methods

Selective laser sintering (SLS) involves rastering a laser over the surface of a powder. Another powder layer is then added and the process repeats. Several materials have been demonstrated; even ceramics or metals can be used if a thermal binder is integrated [172, 174, 175, 226, 227]. Support is provided by the unfused powder of each layer, which is dusted off at removal [172, 174, 227]. Powder particles are taken to the glass transition temperature [176]. Typically an infrared laser is used [176]. Airflow, cooling rate and part geometry can affect accuracy [228]. Large parts may require a long cooling time [228]. Multi-material part delivery has been proposed [230].

Stereolithography (SLA) is based on rastering a laser over the surface of a photopolymer liquid [172, 174, 175, 226, 227]. SLA requires support structures to be built up under overhangs [172, 174, 175, 227]. SLA results in smooth surface finishes [176, 182]. SLA can support multiple colors and graded materials [176]. Laser geometry determines the theoretical minimum feature size; however tiny features may be too fragile [228]. Typically a UV laser is used (for photocuring) [176]. In some cases, the material may be toxic in the liquid state, and thus require careful handling [176].

Fused filament fabrication (FFF), or fused deposition modeling (FDM) involves extruding a heated thermoplastic strand (typically ABS) as a nozzle is rastered over a support table to gradually build up the part [172, 174-176, 228]. Support structures may be required in FDM, depending on part geometry. Multiple materials are possible but not gradient material builds [176]. Support material is required, and may take considerable effort to remove. Dissolvable supports are available in some machines [176, 182]. Support structures are trapped in cavities [228]. Some surface finishing may also be required.

Polyjet printing is a multi-material extrusion process. A heated print head deposits polymers on a support bed [174-176, 226, 228]. The support material is easy to remove. Gradient materials are supported [174]. Note that each layer slightly melts the layer beneath it [176].

3D printing is considered an indirect method, as an inkjet deposits adhesive to bond powder (the powder is laid down as in an SLS machine) [174-176, 226, 228]. This is not to be confused with the colloquial term '3D printing' which typically means either FDM or AM in general. It saves build time to place the thinnest dimension along the (z-axis) build direction, to reduce the total number of layers [226]. Parts are typically fragile, but they can be reinforced with an adhesive [228].

Laminated Object Manufacturing (LOM) involves layering thin sheets [172, 174-176, 226, 228]. The material comes from a roller, unspooling like a paper towel roll, that allows for rapid printing [172, 174-176, 226, 228]. Support material removal requires some effort [228]. Parts are also notably weaker (1/10 yield strength) along the axis of layering.

There are a number of other AM methods. In beam interference solidification, two lasers intersect in a liquid filled vat, causing the material to solidify at that point [231]. Another form of sterolithography applies an infrared laser [231]. In solid ground curing, a physical mask is placed in front of a wide light source to direct light for curing each successive layer [231]. Holographic interference solidification involves projecting a holographic image into liquid polymer and the whole object solidifies [231]. In electrosetting, layers are printed along with electrodes, then electric current is applied to set the powder [231]. Three dimensional welding is applied by a robotic arm that deposits metal in a 3D path with an arc welder [231]. Solid foil polymerization is similar to LOM except that the sheets are UV-curable and set with a UV laser [231]. Laser engineered net shaping (LENS) is a direct metal deposition process, in which metal powder is supplied by a deposition head, and then a separate laser system sinters the powder. One advantage of LENS is direct printing onto a contoured substrate. LENS also supports gradient materials; however, machine and material costs are high [175]. Foam-cut layering has also been presented as a technique for visualization [232, 233]. This might be done with paper also, and although it is a manual technique, it is very low cost [176]. Some specialized SLS machines work with metal powders. Additive manufacture of metal components has been demonstrated with a wide variety of metallic compounds from steel to gold. Crystal lattice structures in metal prints are relatively uncontrolled at this time, and research is ongoing in this area.

Further methods propose rapid manufacture of large scale structures (e.g. houses). One concept employs a gantry for deposition, with a robot for troweling surface detail [234]. In another method, parts are algorithmically segmented, then mortise and tenon features are added for assembly of a part that is larger than the print bed [235]. A hybrid manufacturing technique (e.g. SLA and CNC) can also fabricate parts with superior material properties [236].

3D Scanning is often an enabling technology of AM, as models can be scanned and modified (if necessary) then directly reprinted. In most cases some assumptions of scale and calibration are required [237]. Surface reconstruction varies by algorithm [238], various alternatives have been explored. Some algorithms have proven highly accurate even on complicated surface [239]. Scans also vary by technology; while laser scanning captures surface information, CT or magnetic resonance imaging MRI scans also capture internal structures [175]. Alternative methods include pattern projection, in which distortion of a light pattern projected onto the surface reveals its contours [240]. Pattern projection is static (the subject need not be rotated as is required in laser scanning) [240]. Another approach uses an algorithm to stitch common points of pictures taken at multiple perspectives to form a 3D shape [241], a process that can even be executed on a mobile phone. This method works well for buildings and large structures [241].

Scanning has been incorporated with AM in diverse applications. In dentistry, scanning and AM are applied to form teeth and other prostheses [175]. MRI, coupled with rapid prototyping, was used to develop precise replications of the human vascular system [242]. These can be useful for study or surgical training [242]. A 3D scan of an athlete was also used in simulation then rapid prototyping of high performance sportswear [130].

2.7 Conclusion

Summary of key observations for prototyping

There are numerous established objectives and outcomes of prototyping. Two high level objectives of prototyping are exploration and validation of design concepts. However, prototyping is perhaps most well-known for design refinement. Studies of industry also highlight the critical importance of prototypes for communication, both for gathering usability data from the user and for communicating the concept to other developers. Finally, prototypes are also critical for the active learning of designers and users.

The use of prototypes as a general design tool has been explored in some detail. There are several effective ways to engage with a prototype, although certain activities may be more applicable at one time than another. The research shows that while early prototyping is critical for success, this effect diminishes over time. The use of prototypes for ideation can increase the percentage of functional ideas, versus pure sketching. Although prototypes can actually reduce fixation, due to organic concept evolution, a cumbersome fabrication process has the opposite effect. Receiving outside feedback on prototypes can lead to feature improvement, especially if several are presented in parallel, but this may also increase fixation. Other novel metrics such as number of parts, which is inversely correlated to performance, or interactivity assessment, may also provide insight for evaluating the prototype.

There are a number of strategic techniques to apply prototyping, each with various advantages. Prototypes with reduced requirements can reduce early waste (of resources) but may not provide much detail of manufacturability. Mockups are a powerful tool to rapidly explore concepts and enable communication; however, they may misrepresent physical principles. Isolated subsystem testing can also reduce costs and permit tailored requirements; however, unanticipated needs may be difficult to address. Scaled prototypes can enable testing in cases when a full-scale system might be infeasible; however, significant testing may be required to achieve an accurate model. Iterative prototyping is strongly correlated with performance increase, and although time expense decreases with each iteration, it may cost additional time. Parallel prototyping is correlated with increased performance, but also appears to put additional strain on the design team. Competitive prototyping is analogous to parallel prototyping. However, separate teams each pursue one concept. This approach may reduce ultimate costs and improve quality, but short term costs may rise. Cooperative prototyping can engage end user participation. Virtual prototypes can supply novel data, and drastically reduce prototyping costs; however, significant technical expertise may be required to implement a virtual model. Mixed prototypes provide authentic user interaction at low cost, novel data acquisition, and permit controller design. However, in some cases mixed prototyping may require a skilled operator to implement.

There are numerous fabrication techniques for prototyping, each with various benefits and drawbacks. Component sourcing can play a large factor in costs; typically, COTS components can result in savings. If custom components are required, strategic analysis of in-house versus outsourcing can reduce risk. Handcrafting appears to be the fastest fabrication method; however, it often carries the connotation of low-technology and may not be as effective at eliciting confidence in stakeholders. Two dimensional fabrication is rapid and may produce functional components. The emergence of 2D-to-3D tectonic decomposition methods demonstrates new capabilities of laser-cutting and other 2D methods; however these algorithms are not yet commercialized. There is also a wide selection of additive manufacturing technologies; however, certain capabilities such as gradient materials are not readily represented in commercial CAD software. 3D scanning is often an important extension to additive manufacture, and there are many technologies for surface scanning. There is an opportunity for development of integrated methods to select between scanning, modeling, and additive manufacture tools.

Concluding Remarks and Looking Forward

This review provides an overview and synthesis of current major findings in scientific empirical examinations of prototyping. These studies provide a systematic review of many of the critical variables related to prototyping. Protocol analyses, controlled variable experimentation, and in depth ethnographic reviews of practicing designers have been conducted to provide a clear picture of many of the practices associated with success in a prototyping effort.

Section 1 identifies the high level motivations for implementing prototypes. Section 2 then outlines general precautions and factors that are empirically correlated with successful integration of prototyping into the design process. Section 3 reviews research related to principles or heuristics; Section 4 then provides a set of standalone techniques which could also be combined into a larger strategy for planning a prototyping effort. These techniques have numerous benefits but are generally guidelines for planning a specific prototyping effort and guiding the selection of certain variables (such as fidelity of the representation). These methods are based on empirical studies identifying opportunities to enhance the efficiency of time and resources, and improve data acquisition. Section 5 concludes the review with a summary of fabrication technologies. This last section provides quantitative descriptions of the capabilities and cost of various fabrication technologies to assist in efficient cross-assessment between subtractive fabrication, additive manufacture, outsourcing, and hand crafting.

There are opportunities for seminal work in integrating design science with the DIY movement. This trend is towards the consumer becoming the designer and the manufacturer, and there are many opportunities to explore how design research may systematically enable DIY design. In parallel with this, it appears that there is an enormous untapped potential for rapid mockup handcrafting, and also with distributed task decomposition (crowdsourcing and crowdcrafting) in the prototyping literature and methodologies. How can cognitive processes, advanced ideation methods (such as biological analogy methods), and hand fabrication be mapped in empirical studies? This might include protocol analysis observing fabrication in situ, neurological analysis of prototyping activities, study of crowdsourced design, and even crowdsourced design research.

It is also clear that there is a need for design tools that capture the full capabilities of additive manufacturing (some of which may be yet to be discovered). Several objectives for development which have been provided are: intuitive human interfacing with CAD tools for complex design features, micro- to-meso- features, design and modeling using gradient materials, algorithmic model construction, and integration of multi-domain functionality.

Chapter 3: A Hybrid Design Prototyping Tool - Designing Biologically Inspired Leaf Structures: Computational Geometric Transport Analysis of Volume-to-Point Flow Channels[1]

OPENING REMARKS

This chapter explores a detailed design case study of executing a hybrid technique for prototyping. The effectiveness of a full-fidelity, finite element model is compared to a relaxed requirement virtual modeling technique. Both methods are applied for design of an efficient cooling channel array. The novel method which is developed in this chapter demonstrates the capability of combining individual techniques for prototyping. In this case, combining requirement relaxation is combined with virtual prototyping resulting in a novel biologically-inspired design, as well as reduced modeling complexity. The approach demonstrates that critical design decisions can be made using a relaxed virtual prototype. Using the relaxed requirement virtual prototype, it is possible to compare several alternative designs in parallel with substantially less computational expense than a full FEM would require.

3.1 INTRODUCTION: THE VOLUME-TO-POINT FLOW PROBLEM

A common feature among certain natural systems, such as arteries, lightning, bronchial airways, leaves, and watersheds, is a pseudo fractal branching structure) [243] This commonality may be due to the fact that these systems solve a similar type of problem, i.e., the transport of energy or matter from a distributed arrangement (area or volume) to a single point (sink) [244]. Figure 3.1 shows an example natural system. A

1 B. Camburn, K. Otto, D. Jensen, R. Crawford, and K. Wood, "Designing biologically inspired leaf structures: computational geometric transport analysis of volume-to-point flow channels," Engineering with Computers, 2014.

Contributions: B Camburn research concept, lead author, experimental execution; K. Otto, D. Jensen, R. Crawford, and K. Wood provided guidance and editing.

characteristic of these systems is a network flow field that guides the energy or matter to a sink point [244].

Figure 3.1: Example of a volume-to-point flow system - a leaf and its veins.

A number of geometric layout choices for the channels are possible for the path configurations when solving volume-to-point flow problems. For designers, it would be convenient if an effective layout could be found easily and repeatably. A review of the literature indicates a need for more advanced and repeatable approaches for understanding how to lay out channels to optimize flow.

There are a number of approaches to solving volume-to-point flow problems. One area focuses on the use of biological analogy to solve such problems. In particular, truncated pseudo-fractal geometries have been proposed for channel cooling [244-248]. These types of geometries, known as Constructal configurations, were developed from a cellular optimization method and exhibit a pseudo-fractal structure [244]. An alternative analysis that takes into account the global topology of flow configurations can offer new insight into these systems.

This work proposes a novel metric, path length, defined to be the average distance travelled by fluid or energy from the starting point in a substrate to the sink. This metric provides the basis for a quantitative approach to evaluate configurations for volume-to-point flow problems. The path length metric arises from basic transport theory and inspires the design of novel configurations for volume-to-point flow problems. The goal of these configurations is to provide near-minimum path length. Computational analysis is used below, to demonstrate that these configurations are more effective than state-of-the-art approaches for the given problem.

3.2 Previous work

Background: Biological Analogy and Fractal Representations

The term homoplasy, which is sometimes called convergent evolution, is used to describe unrelated organisms that develop similar traits. The extensive homoplasy of the pseudo-fractal architectural structures in nature strongly indicates that this solution form is very effective for volume-to-point flow problems [249]. Thus, due to their potential optimality, pseudo-fractal structures may provide appropriate analogies for solving such design problems.

Analogical methods have been shown to be effective in the creation of novel solutions to design problems in the engineering knowledge domain [250-263]. One example is a method of seeding mind-maps with biological analogies for the solution [264]. In studies on biological analogy, it has been shown that exposure to biologically inspired design methods can systematically enhance creativity in designers [261]. Further, it has been found that the biological analogies used for solution generation can entail transfer of knowledge of causal mechanisms or knowledge for problem decomposition [262].

Solution of a biologically inspired problem begins by first generalizing the problem form [261]. Bejan executed this approach to generalize the volume-to-point flow problem, leading to the identification of the Constructal structure as an analogous solution [244]. The abstraction approach simultaneously re-represents the design problem and provides initial understanding. Subsequently, one must extract the general principle that occurs in the natural systems, allowing for direct replication of the natural analogy into the human-design frame [261]. A principle can be observed in these systems, which is minimization of transport distance. When other variables (such as channel cross section properties) are held constant, the minimization of path length is effectively the minimization of the total quantity of resistance that must be overcome when moving energy or matter from a volume to a point. This minimization is an instance of finding the "path of least resistance," thereby achieving the most effective use of available transport energy.

Fractal representations in engineering analysis are well known for a number of physical domains [245, 246, 265-272]. Several authors have published work on the characterization of the fractal form of various naturally emergent volume-to-point flow systems, especially relating to humanoid cardiovascular systems, e.g., [273]. This research clearly classifies the fractal number, examines the levels before truncation and determines geometric ratios between branches. Several authors have been conducting ongoing research into the truncated fractal, or Constructal, volume-to-point channels [243-246, 249, 265-268, 270, 271, 274, 275]. These papers thoroughly examine and expand the Constructal theory; however, it may be that additional properties can be examined to expand understanding of system-wide resistance to flow.

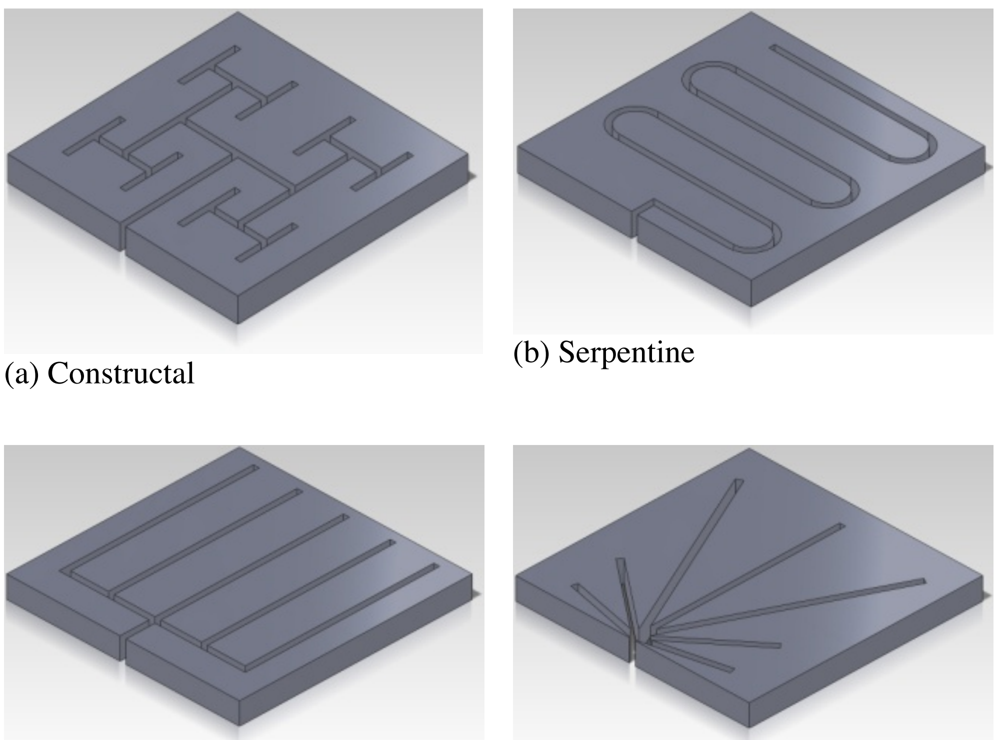
Constructal Theory and Alternatives

Previous research has explored fractal structures in nature and their application to the volume-to-point flow problem. Bejan, in particular, has developed a pseudo-fractal Constructal geometry for volume-to-point cooling problems [276]. Constructal theory begins with the assumption that the pseudo-fractal structures in nature have undergone sequential improvement, and that likewise, an optimization procedure should produce an analogous configuration. Bejan's analytical model optimizes the local heat transfer cellular building block [244]. In contrast, this chapter explores the global structure through a geometric analysis for developing optimal flow channel designs as an alternative approach to mimic biological pseudo-fractal systems.

Bejan proposed the Constructal Theory, which states that, the pseudo-fractal structures observed in nature result from a directional optimization process that moves from a smaller scale towards a system-level scale [244]. The implication is that pseudo-fractal structures are the result of an iterative bottom-up optimization process for volume-to-point flow. Based on his observations of nature, Bejan proposed a flow principle: "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access (less resistance) to the imposed (global) currents that flow through it" [244]. This principle includes the assumption that flow rates inside the channel are much higher than that of the substrate volume in which energy is generated (i.e. channel resistance is very low). An assumption is made for Constructal analysis that the optimal flow configuration can be found by minimizing the temperature differences between directly adjacent elements and that this corresponds to minimizing resistance, for the volume-to-point cooling problem. This assumption has merit. However, it does not appear to take into account effects from distant cells, or effects due to the global position of each differential element with respect to the sink location. Therefore it may tend to create flow channel configurations that have locally optimal characteristics as opposed to ensuring solutions that move toward global optimization.

Other researchers have considered alternate solutions to the volume-to-point flow problem [245-247]. Zhang compared the analytically determined performance of a serpentine channel configuration to that of Bejan's Constructal configuration (see Figure 3.2) [250]. Figure 3.3 shows a plot of the difference between minimum and maximum wall temperature versus heat generation value. He found that the Constructal design results in a more uniform wall temperature, indicating that the plate is more evenly cooled. Temperature difference (ΔT) versus heat flux ($\dot{q}$) provides one measure of effectiveness of cooling performance. Figure 3.2 illustrates the Constructal and serpentine configurations.

Several authors compared the performance of serpentine and fractal configurations via empirical studies [245, 277] in fluid flow systems. They concluded that the Constructal configuration (Figure 3.2a) is superior to parallel lines for fluid flow problems. The parallel lines configuration is shown in Figure 3.2c. Several papers explore a variant of the Constructal geometry that is circular in form [274, 278]. This circular geometry had been developed by Wechsatol et al. to minimize fluid pressure in channel flows [248]. Chen et al. consider the Constructal configuration for a methanol reformer design problem. In this system there are a separate inlet and outlet. The overall functionality is similar to the volume-to-point flow problem, and they also find the Constructal geometry to outperform the serpentine configuration [278]. Additionally, Chen et al. find the rectangular Constructal form to outperform the serpentine configuration in terms of pressure loss for a single inlet, single outlet flow system [274]. Analyses have considered the number of branching levels in a Constructal form [278], and in alternate flow problems including line to line flow [276]. Some of these analyses consider similar geometries; however, they are largely investigations for fluid flow. This work analyzes conductive heat transfer. Also in most of the analyses, channel width can vary throughout the geometry. Each geometry should have the same surface area (driven by channel width) and length of channel within the plate, as these geometric constraints correspond to certain manufacturing constraints. There do not appear to be any papers that consider the Leaf configuration in Figure 3.2d. The following sections will pursue such a geometry.



(a) Constructal

(b) Serpentine

(c) Parallel Lines

(d) Leaf

Figure 3.2: CAD rendering of each configuration. In the FEM, the voids in the plates are filled with cooling channel. The cooling channel is kept at constant temperature at the small opening on the wall. (See Figure 3.4.)

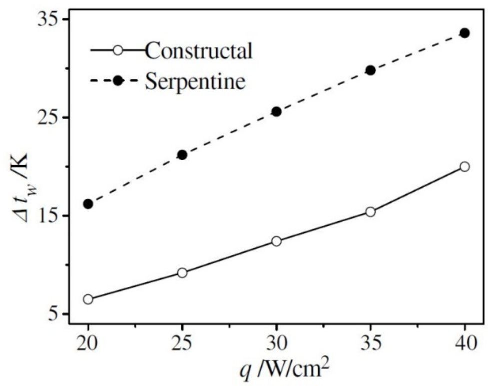


Figure 3.3: Difference between maximum and minimum wall temperature values as a function of heat generation for Constructal versus serpentine configurations [28].

3.3 Research Approach

In this chapter, analytical and computational evaluation are used to determine the effectiveness in conductive heat transfer of geometrically different arrangements of cooling channels. The channel arrangements each have the same volume and length. They conduct heat from a substrate volume, which has a lower thermal conductivity than the channels and is homogenously producing heat. The heat is conducted to a sink point that is maintained at constant temperature (Figure 3.4). Constant temperature approximates a rapid convective cooling condition at that point. This condition might be found at the interface of the chip and a heat sink. Because the transport efficiency of each arrangement is different, the maximum plate temperature at steady-state is higher for a less efficient arrangement. This example of volume-to-point flow is known as the microchip-cooling problem. This design problem is a standard benchmark for diffusive channel design analysis [244, 249, 250].

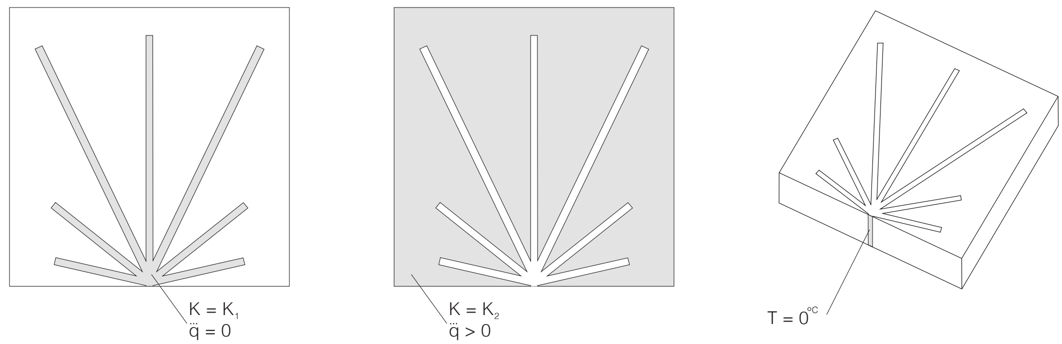


Figure 3.4: Detailed model of the (leaf) system with boundary conditions. Channels (left) have thermal conductivity K1; plates (center) have thermal conductivity K2 and nonzero heat generation per unit volume; and the bottom surface of the channel (right) is at constant temperature 0°C. All exterior surfaces are adiabatic (q*=0)

In this chapter cooling performance analysis methods are used to compare several channel configurations. Path length analysis is proposed as a geometric approach that simplifies the evaluation, and ultimately the design process, for volume-to-point flow channel configurations. Specifically, path length minimization is used as a critical requirement in the design of channel configurations. This metric is used to compare different channel configurations by inspecting performance results from the finite element method (FEM).

The system schematic, Figure 3.4, shows boundary conditions applied to the FEM models. Although only one configuration is shown, analogous conditions were used for each model. The mesh is held at constant temperature at the sink (as in Figure 3.4, right) and heated with constant heat generation throughout the entire sub-volume. The channels were not heated. Four geometries were constructed in a CAD program and imported into computational (FEM) software for evaluation. The cooling channel lengths of the different configurations agree to within 0.1%. Negligible contact resistance between the cooling channel and the plate is assumed. A large range of conduction coefficients was considered to effectively model different thermal resistances within the cooling system.

The analyzed geometries are introduced above in Figure 3.2. The Constructal form is a truncated fractal, i.e., a fractal that terminates after a certain number of repetitions or levels. Four iterations of branching are used herein. The Constructal configuration from Figure 3.2a is generally considered to be a benchmark optimal configuration for volume-to-point flow on a square plate [244]. The serpentine and parallel line geometries (Figures 3.2b and 3.2c) were also considered from relevant literature [243-246, 249, 265-268, 270, 271, 274, 275]. The leaf geometry is novel to this work and was developed based on path length analysis (Figure 3.2d).

Metrics

A set of meaningful metrics and design variables are chosen for each analysis approach, as summarized in Table 3.1. Average path length and maximum plate temperature are used to evaluate the geometries in the path length analysis and finite element analysis, respectively. The hypothesis that the geometry with the shortest path length also has the best transport efficiency, and thus better cooling performance, is tested. From a global metric perspective, the cooling channel configuration with the lowest maximum plate temperature in steady-state conditions is considered to have the best cooling performance. The channel depth, width and total channel length are held constant to effectively compare different channel configurations. For this study, the geometric arrangement of the cooling channels in the plate is the design variable of focus. The material properties and heat generation values are varied in the FEM. These parameters are varied within the FEM. The performance values are compared to the computed path length. Path length is a metric for the average transport distance within a volume-to-point flow problem and is described in greater detail in the rest of Section 3. From the comparison of FEM and path length, the range of physical conditions over which the path length can be used to predict performance is determined.

		Path Length	**FEM**
Performance Metric		Average path length	Maximum plate temperature
Design Variables	Volume of cooling channel	Constant	Constant
	Surface area of cooling channel	Constant	Constant
	Plate volume	Constant	Constant
	Channel configuration	Varied	Varied
	Plate and channel material properties	N/A	Varied
	Volumetric heating values	N/A	Varied

Table 3.1: Metrics and design variables.

Path Length Analysis Method

To visualize path length, suppose a heat generating volume is replaced with a densely packed cloud of points in space, and the cooling channel is replaced with another set of points in space. Assume that at discrete time steps, the points that represent the plate are producing packets of energy, heat, or fluid flow. Theoretically, these packets will travel along some path between each source point and the sink point. The path length is simply the geometric length of this transport path, averaged across all of the points in the cloud. The novel assumption of path length analysis is that each packet will flow along the shortest path to the nearest segment of channel, and then inside the channel, via the shortest path, to the exit. The path followed by a single point source is shown in Figure 3.5 for an example channel configuration. The assumption that flow occurs in this way arises from the observation that flow follows the path of least resistance, and the fact that the channel resistance is much lower than that of the plate [244]. Several supportive arguments for the construction of this model of the generic volume to a point transport scenario are discussed below.

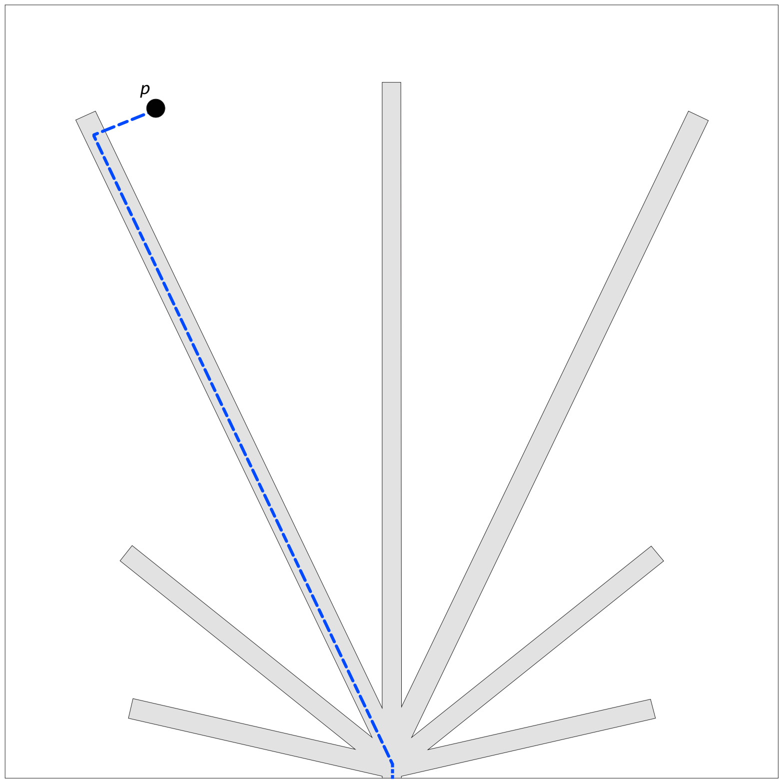


Figure 3.5: Example of path length (for a single point in the leaf configuration), highlighted with the blue dotted line, between a single point source, p, and the sink.

Analytical Foundations (Transport and Lumped Resistance)

A configuration with a high thermal resistance will result in a high maximum plate temperature [244]. Equation 3.1 demonstrates that thermal resistance is proportional to transport path length. To efficiently conduct heat from a distributed volume to a single point, the overall thermal flow resistance must be minimized. Based on the heat conduction equation between two surfaces separated by a material layer, the thermal resistance between the two points is proportional to the distance between those two points [279]:

$$q = -\frac{KA}{L}(T_H - T_C)$$
$$R_C = \frac{L}{kA}$$
$$R_C \propto L \tag{3.1}$$

where q is the heat flux, K is the thermal conductivity, A is conduction area perpendicular to the direction of heat transfer, L is the conduction distance, TH is the hot side temperature, TC is the cold side temperature, and R_C is thermal resistance.

Note that different configurations with the same length of channel can still have different path lengths. This is because, due to the different channel configurations, there are different distances between the heat generation points located throughout the plate and the channels. In this design scenario, L is the dominant component. This holds in many natural systems such as the leaf [249], and engineering problems such as conductive microchip cooling [244].

Algorithm to Compute Path length

In the path length analysis method, the heating volume and the cooling channel are represented as a two dimensional matrix of point clouds. Using the standard discretization process, similar to that used in FEM, the volume is represented as a set of differential subvolumes. Each subvolume is then represented as a point source.

It is not necessary to consider the amount of heat generated at each point for path length analysis. FEM testing showed that $\ddot{q}$, volumetric heat generation, does not affect the contours of the temperature distribution on the plate, only the magnitude, and it does this in equal proportions for each configuration.

The algorithm for calculating average path length for a configuration consists of representing the geometry as a point cloud and then performing a series of geometric distance calculations using these points. The steps in the algorithm are detailed in Table 3.2. The appropriate density of approximation points (similar to FEM discretization density) is determined through convergence analysis. To perform convergence analysis, the matrix of points is redefined, increasing the number of points per unit area, and then recalculating the path length. This is repeated until the variance in average path length from a discretization density increase of one order of magnitude is less than some epsilon value, in this case, a tenth of a percent of the average path length.

(1a) Generate the Substrate Point Grid	Generate a set of m evenly distributed points, over an area, to represent the substrate. Store the coordinates of each point in a 2×m matrix, [S]. Figure 3.6a (top)
(1b) Generate the Channel Points	Generate a set of n evenly distributed points, along lines, to represent the cooling channel. Store the coordinates of each point, in a 2×n matrix, [PL] Figure 3.6a (bottom)
(2) Determine the Endo-Channel Path Lengths	Geometrically calculate the distance along the channel from each point on the channel line to the sink.
(3) Compute the Exo-Channel Path Length Values	For each point in the substrate grid, calculate the distance to the first point in [PL] using the distance equation, $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. Store this distance as PLEX_min. Calculate the distance to the next point in [PL] from the current substrate point, and replace PLEX_min with this value if it is smaller than the current value for PLEX_min. Repeat for all points in PL. Then PLEX_min is stored in a new matrix as the exochannel path length for that point on the substrate. Add the distance, found in 2, for the point at PLEX_min along the channel from that closest point to the sink. Repeat for every point on the substrate matrix. Figure 3.6b
(4) Compute the Average Total Path Length	Sum the distance found for each point in step 3 and divide by n to determine the average path length.

Table 3.2: Steps to Compute Path Length.

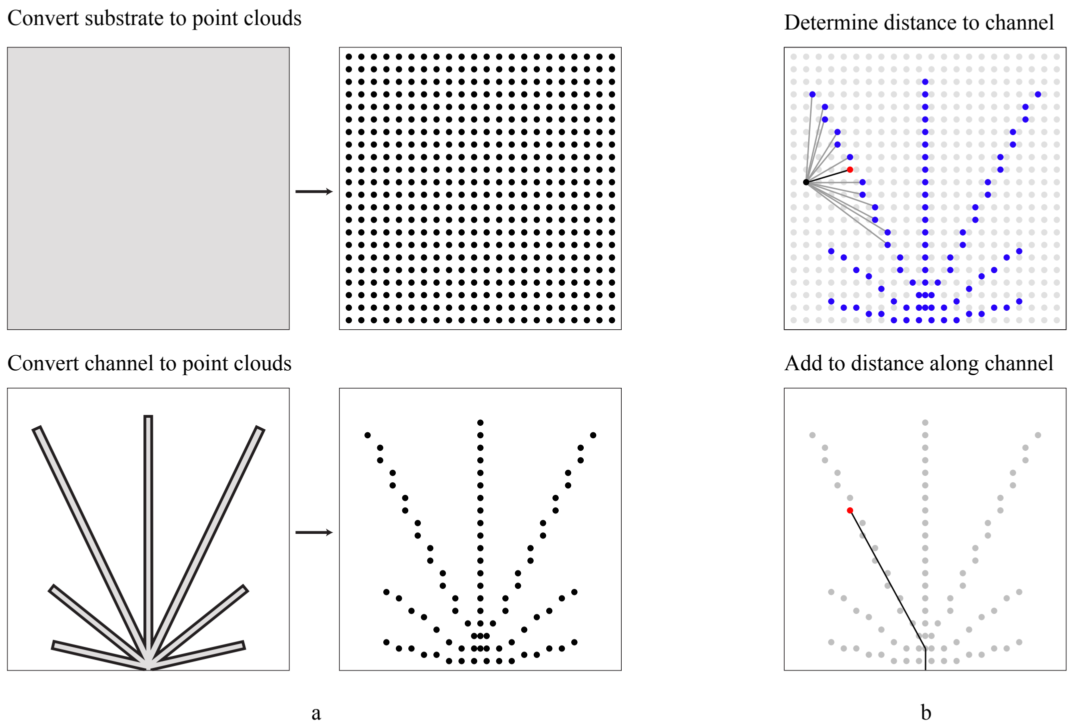


Figure 3.6: (a) Graphical elaboration of step 1 of path length algorithm from Table 3.2. (b) Demonstrates path length calculation for a single point from step 3 of path length algorithm from Table 3.2

Verification of Discretization for Path Length Analysis

To determine if the coded implementation of the method given in Table 3.2 is accurate, a basic example is evaluated. The path length for a simple square geometry (Figure 3.7) was computed in closed form as well as using the path length algorithm. The cooling channel in this configuration is a straight line along the base of the square plate, and the sink is at the center of the channel. The average distance from any point to the channel is half the plate height, and the average endo-channel path length is one quarter of the edge length. Thus, the closed form average total path length is exactly 75% of the edge length. Implementation of the steps in Table 3.2, using MATLAB (MathWorks®

Natick, MA, USA), finds the average total path length to be 75.025% of the edge length. The algorithm exhibits a small discretization error of approximately 0.03%.

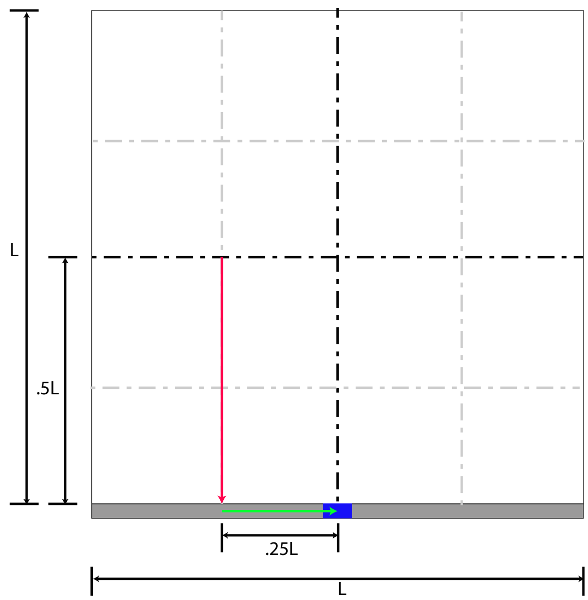


Figure 3.7: Geometry of the example problem. The channel is shown in grey, the average distance to channel is shown in red, the average distance along the channel is shown in green, and the blue square is the sink.

3.4 Computational Model Theory

This section describes validation of the path length method by comparison with finite-element analysis of a heat transfer problem. In this problem, heat is conducted through two materials to a sink. The first material is the homogeneous heat generating plate (Figure 3.4 center), and the second is the cooling channel (Figure 3.4 left). In the computational model, the channel component is assigned a high value of thermal conductivity while the substrate has a lower value of thermal conductivity. The small opening where the channel terminates is maintained at a constant temperature (0° C) to simulate connection to a heat sink or coolant at steady-state. The channels of various geometrical configurations conduct heat to this sink area. The plate is adiabatic at all surfaces. The constant temperature surface on the channel bottom, Figure 3.4 (right), acts as a sink. Every geometric configuration has the same volume and surface area of cooling channel. Various values of thermal conductivity are employed. Heat generation is also varied to demonstrate that the changes are linear, as stated above. Each analysis terminates when steady state conditions are reached. The model is effectively two-dimensional as there is no variation in the z dimension (perpendicular to the plate). Table 3.3 summarizes the properties used for the finite element analyses. The values that are not varied in the model, such as plate dimension, are those for which heat transfer phenomena are scalable; thus, the method remains generalizable.

Geometry	10x10x1 cm3 plate
Thermal Conductivity of Plate	K_1
Thermal Conductivity of Channel	K_2, where ($K_2 > K_1$)
Avg. Mesh Length (after convergence)	0.3 cm
Cooling Channel Volume	1,245 cm3
Cooling Channel Surface Area	12,250 cm2

Table 3.3: Properties of the FEM.

Computational model theory

Finite element modeling of a heat transfer problem is a process of discretizing a volume into a network of approximately differential unit volumes and calculating heat transfer between them. First a wire-frame model is created from an imported 3D geometry, in this case the channels and plate. The finite element discretization involves the creation of three dimensional elements where the equilibrium equations will be enforced. These elements are connected to adjacent elements at nodes where compatibility will be enforced so that the continuity of the solution of the differential equations of equilibrium can be maintained. This results in a matrix equation for the heat transfer characteristics of the system. Finally a Newton-Raphson type sparse solver algorithm is applied to determine temperatures throughout the system. A flowchart of the over-all process applied can be seen in Figure 3.8.

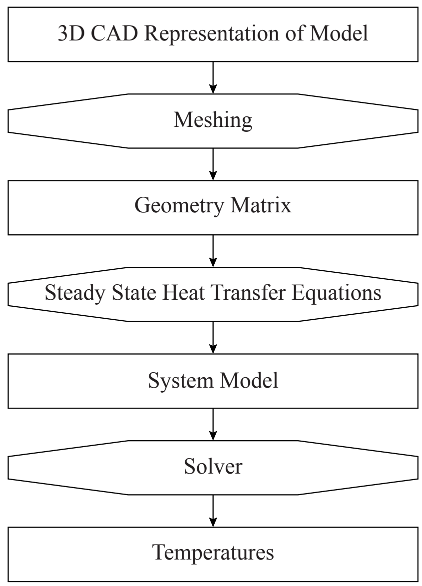


Figure 3.8: Flowchart representation of a method for finite element heat transfer modeling

Meshing

Meshing is the first step in finite element modeling (FEM) processing. The 3D geometry of the channels is imported as parametric curves. A mesh representation of the object is created by modeling geometric features as elements that have nodes and edges connecting these nodes. The meshing algorithm operates by supplying a generic guess at a mesh structure and then iteratively testing this against certain error criteria and continually updating the mesh. When the error criteria have converged, the system finalizes the mesh for analysis. The metrics are the error of the mesh surface (difference to actual), the ratio of side lengths of one element to another, and a range of acceptable angles of intersection (between two lines in the mesh) [280]. The equilibrium equations are enforced in each element and the results extrapolated to the nodes that connect the elements. The values of the dependent variables are calculated at the nodes (often called degrees of freedom). This ensures a form of continuity of the field variables across the plate, as the elements share adjoining nodes. For this work, the 8 Node Brick type element was selected as the base unit due to its reliability for heat transfer modeling [281, 282]. A representation of the wireframe of an 8 Node Brick element can be seen in Figure 3.9.

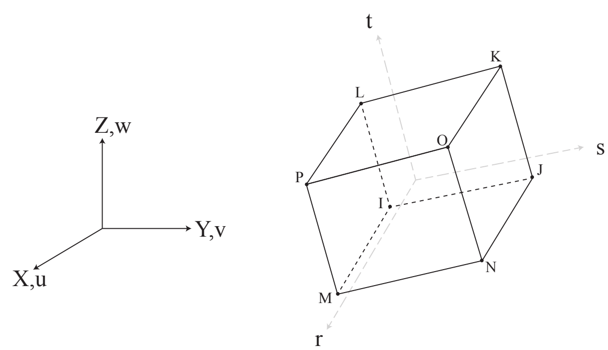


Figure 3.9: Wireframe of 8 Node Brick element.

The equations for this geometry, Figure 3.9, are given as follows:

$$\begin{aligned} T = \frac{1}{8}(&T_I(1-s)(1-t)(1-r) + T_J(1+s)(1-t)(1-r) \\ &+T_K(1+s)(1+t)(1-r) + T_L(1-s)(1+t)(1-r) \\ &+T_M(1+s)(1-t)(1+r) + T_N(1+s)(1-t)(1+r) \\ &+T_O(1+s)(1+t)(1+r) + T_P(1-s)(1+t)(1+r) \end{aligned} \tag{3.2}$$

where T_I, T_J, T_K, T_L, T_M, T_N, T_O, and T_P are the temperatures at each of those points (I through P), respectively [42-Chapter 12].

Unit Volume Model

Once the mesh is developed, the heat equation is applied across the mesh. Applying the first law of thermodynamics to a control volume and combining with

Fourier's law relating heat flux to thermal gradients develops the result for steady-state conduction for a unit volume, in this case, a single brick node 8 element:

$$0 = \ddot{q} + \frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) \quad (3.3)$$

where $\ddot{q}$ is the heat generation per unit volume, K_x, K_y, K_z are thermal conductivities in x, y, and z respectively, T is temperature (=T(x,y,z)).

Two types of boundary conditions are applied in the model. Constant temperature is applied at the base of the channel, and zero heat flux (insulation) is applied on external surfaces. Equation 5 is the form for specified temperature acting on a surface S1:

$$T = T^* \quad (3.4)$$

where T^* is the specified temperature acting on S1.

The second boundary condition is for a specified heat flux. Equation 6 is the form for specified heat flow acting of a surface S2.

$$\{q\}^T\{\eta\} = -q^* \quad (3.5)$$

where $\{\eta\}$ is a unit outward normal vector, and q^* is the specified heat flux through the surface S2.

Full System Model

The mesh structure, described above, connects each finite element to a fixed number of adjacent neighbors. Each node is completely surrounded by either boundary conditions or neighboring nodes. Thus, the heat flux leaving one node is equivalent to the heat flux entering adjacent nodes. Summing these relationships over all nodes yields:

$$\sum_{m=1}^{n}[K_e]\{T\} = \sum_{m=1}^{n}\{Q_e^f\} + \{Q_e^g\} \quad (3.6)$$

where:

$$[K_e] = \int_{vol}\left[\begin{Bmatrix}\frac{\partial}{\partial x}\\ \frac{\partial}{\partial y}\\ \frac{\partial}{\partial z}\end{Bmatrix}\{N\}T\right]^T \begin{bmatrix}K_x & 0 & 0\\ 0 & K_y & 0\\ 0 & 0 & K_z\end{bmatrix}\begin{Bmatrix}\frac{\partial}{\partial x}\\ \frac{\partial}{\partial y}\\ \frac{\partial}{\partial z}\end{Bmatrix}\{N\}Td(vol) = \textit{element conductivity matrix},$$

$T = \{N\}^T\{T_e\}$ = *temperature variance in space,*

$\{N\} = \{N(x,y,z)\}$ = *element shape functions (see 4.1.1),*

n = *the number of nodes,*

$\{T_e\}$ = *nodal temperature vector,*

$Q_e^f = \int_{S_2} q^*\{N\}(S_2)$ = *element mass flux vector (for constant flux at a surface),*

$Q_e^g = \int_{vol} \ddot{q}\{N\}d(vol)$ = *element heat generation load,*

The integrals are solved at each node using a Gauss numerical integration (Equation 9):

$$\iiint_{-1}^{1} \mathrm{f(x,y,z)dxdydz} = \sum_{k=1}^{n}\sum_{j=1}^{m}\sum_{i=1}^{l} \mathrm{H_k H_j H_u f(x_i y_j z_k)} \qquad (3.7)$$

where: $f(x,y,z)$ *is a generic function (in this case, the integrand of* $[K_e]$) *, n,m,l are the number of integration points in each dimension, and* H_k, H_j, H_u *are a weighting factor for integration approximation [280].*

System matrices are then passed into the solver.

Solver

The system of simultaneous linear equations generated from the heat transfer model above is solved using a direct elimination process. This is largely a Gaussian elimination that involves solving for the unknown vector, generally {u}; which is in this case, T. [K] is a matrix that results from the integral of the differentials of the shape functions and thermal conductivities. For heat transfer applications [F] is analogous to [Q], the vector representing the discretized heat sources.

$$[K]\{u\}=[F] \tag{3.8}$$

The direct elimination process involves decomposition of the matrix [K] into lower and upper triangular matrices, [K]=[L][U]. Forward and backward substitutions or passes are made to solve for {u} itself.

Comparison to Analytical Solution

To validate the computational solutions against well-established analytical methods, a simple configuration was modeled both analytically and with FEM software (ANSYS Mechanical, Canonsburg, PA) [279]. The configuration consists of a plate with fixed temperatures on each side, internal heat generation and adiabatic conditions on the top, bottom, front and back. The plate is 1x1x0.1 cm^3. The temperature of the plate varies in the horizontal direction only. In this example problem, the left surface is maintained at a constant 80° C, and the right surface is maintained at a constant 20° C. The thermal conductivity of the plate is $1\,\frac{W}{mK}$. The FEM model has three degrees of freedom, so 8 node brick elements were used [155, 281, 282].

The analytical solution for temperature as a function of penetration depth between the two walls is:

$$T=\frac{\dot{q}L^2}{2K}\left[\frac{x}{L}-\left(\frac{x}{L}\right)^2\right]-\frac{(T_H-T_C)}{L}x+T_H \tag{3.9}$$

where $\dot{q}$ is the heat generation rate per unit length, L the distance between the walls, K is the thermal conductivity, x is the penetration depth, T_H is the hot wall temperature, and T_C is the cooler wall temperature [279].

The maximum plate temperatures for several values of heat generation are shown for the FEM and the analytical solutions in Table 3.4. The maximum difference between the analytical and computational solution was found to be 0.03%.

Heat Generation	0$\frac{W}{m^3}$	5X105$\frac{W}{m^3}$	1X106$\frac{W}{m^3}$	2x106$\frac{W}{m^3}$	5X106$\frac{W}{m^3}$	1X107$\frac{W}{m^3}$
Analytical	80.0000°C	80.0000°C	80.0000°C	84.0000°C	116.1000°C	176.8000°C
FEM	80.0000°C	80.0000°C	80.0000°C	83.9965°C	116.1110°C	176.8680°C
Error	0.0000%	0.0000%	0.0000%	0.0040%	0.0090%	0.0300%

Table 3.4: Maximum plate temperature in a volumetrically heated plate from analytical and FEM solutions.

Variance of Sink Temperature

The temperature of the sink area was varied to determine its correlation to performance results. In this study, it was found that the results, temperature contour and maximum plate temperature, scale proportionally with changes in the sink temperature. Thus, performance values are reported at one sink temperature.

Convergence of to Mesh Density

The sensitivity of the maximum temperature in each model to FEM mesh density was determined by studying five mesh sizes of increasing density for each model. These variations spanned a full order of magnitude in mesh size, which was sufficient, as the maximum temperature of the plate did not vary by more than 1% as the mesh size decreased (over the entire order of magnitude shift), i.e. the solution was convergent. Figure 3.10 shows an example of a mesh geometry.

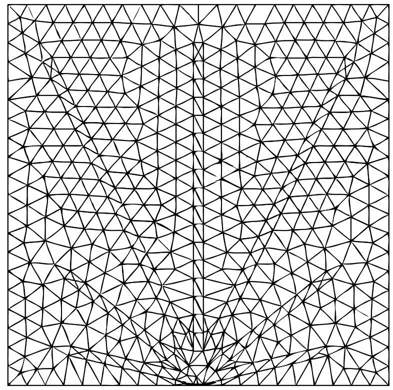


Figure 3.10: Example of meshed geometry (leaf) for plate and channel assembly (1592 nodes).

3.5 Results

In this section the results from path length analysis are compared to those from FEM simulations to establish the viability of the path length approach for evaluating flow channel geometry.

Computational Model Results

Results from 56 unique finite element models are shown in Tables 3.5 and 3.6. These tables present the steady state maximum plate temperature occurring in each of the geometries over a variety of different thermal conductivities (Table 3.5) and applied volumetric heat generation values (Table 3.6). As noted in the previous section, shifts in heat generation values result in linearly proportional changes to the maximum temperature. Thus the morphology of temperature contours is independent of heat generation intensity for this particular problem.

The FEM results indicate that the leaf geometry performs best (has the lowest maximum temperature). The remaining results match those from the literature in that the Constructal configuration performs better than the serpentine configuration [244, 247, 250, 252, 272, 276, 278]. The direct comparison of other configurations, such as the leaf configuration to the Constructal configuration, is novel to this analysis (example in Figure 3.11). On average the leaf geometry cools the plate to a temperature 36% lower than the basic, serpentine configuration, while the Constructal geometry only provides a 14% improvement over the serpentine.

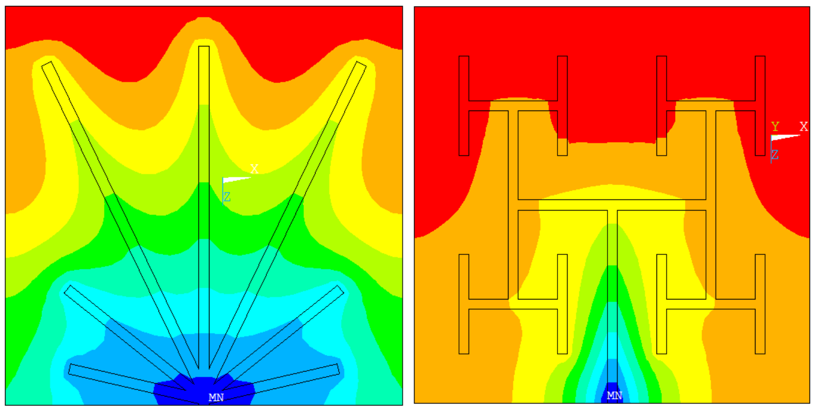


Figure 3.11: FEM contour plots of temperature with $K_1 = 1 \frac{W}{mK}$ and $K_2 = 100 \frac{W}{mK}$ and $\ddot{q}$ = 5X105 $\frac{W}{m^3}$ for the Leaf (left), with maximum temperature of 355 °C; and Constructal (right), with maximum temperature of 773 °C.

$\ddot{q} = 500000 \frac{W}{m^3}$					
Form	K1/K2 = 1	K1/K2 = 1/2	K1/K2 = 1/10	K1/K2 = 1/50	K1/K2 = 1/100
Constructal	1190000	5106	2870	1184	773
Serpentine	1190000	5126	3401	1993	1537
Parallel	1190000	5035	2588	833	477
Leaf	1190000	4299	1653	554	355

Table 3.5: Maximum steady state plate temperature, constant $\ddot{q}$, varying conductivities (bold indicates lowest temperature). Note that K1/K2 = 1 is the condition of no channel cooling effects.

$K_1 = 149\ \frac{W}{mK}$, $K_2 = 401\ \frac{W}{mK}$ (K1/K2 = 1.49/4.01)			
Form	$\dddot{q} = 1000\ \frac{W}{m^3}$	$\dddot{q} = 10000\ \frac{W}{m^3}$	$\dddot{q} = 10000000\ \frac{W}{m^3}$
Constructal	0.063	6.33	633
Serpentine	0.065	6.45	645
Parallel	0.062	6.20	620
Leaf	0.049	4.89	489

Table 3.6: Maximum steady state plate temperature (°C), constant thermal conductivity, varying $\dddot{q}$ values, the boundary conditions for this analysis are as in Figure 3.4. The K1,2 values are for silicon and copper respectively

Figure 3.12 shows thermal gradient vector plots. The flow is towards the channel, then along the channel towards the constant temperature sink for the cooled (left and right) configurations. The uncooled, channel-less geometry in the center demonstrates the natural flow of heat when the entire volume has a constant thermal conductivity. Note that the channels in the leaf plot are normal to the flux vectors seen on the uncooled plate. The most rapid heat flow is in the channels, and this flow aligns with the natural contour for the leaf geometry. This occurs only in the leaf configuration. For the parallel lines configuration, a portion of the channel flow is perpendicular to the natural gradient. Therefore the thermal resistance of the parallel lines should be greater for conductive cooling. This observation is in accordance with the cooling performances of these different geometries.

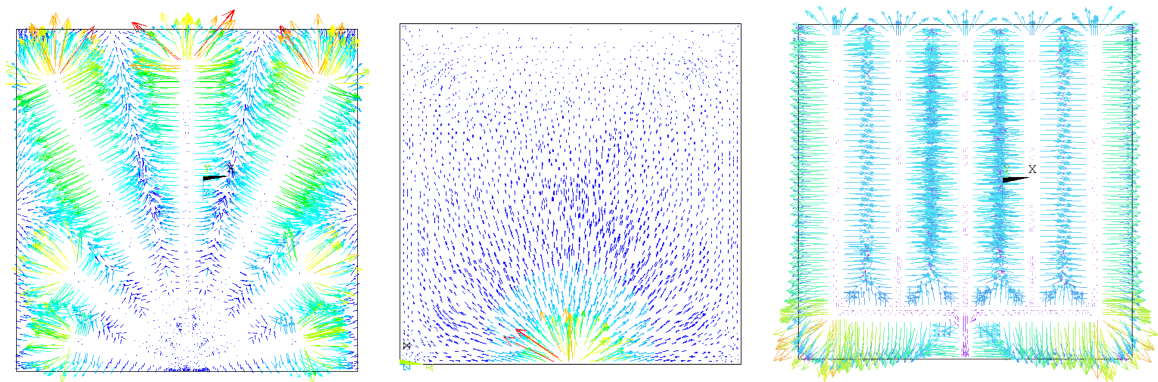


Figure 3.12: Thermal gradient vector plots for the (from left to right) leaf geometry, uncooled plate, and parallel lines geometry

Path Length Results

The geometric path lengths of the cooling channel configurations are shown in Table 3.7. The average total path length of the leaf configuration is the least of the four geometries at 6.5 cm. It is interesting to note that the absolute minimum path length is a straight line from each point to the exit. This value is 5.95 cm for the plate geometry used herein. This minimum length can be calculated by modifying the algorithm from Table 3.2 such that the channel point cloud is replaced with a single point at the sink. The heat flow vectors in Figure 3.12 (center) demonstrate the path vectors in this minimum case. However, in Figure 3.12 (center), flow is very ineffective as there is no channel to accelerate flow. The advantage of a channel with a small path length is that the channel is aligned with vectors along the minimum path. In contrast, other channel configurations carry the flow along directions divergent from the optimal path. This leads to a certain principle: to minimize volume-to-point flow resistance, maximize the alignment of the channel with the natural (diffusion only) flow vectors.

The leaf configuration is an embodiment of the above principle. There is a fascinating resemblance between the biological leaf-veins from Figure 3.1 and the thermal gradient plots from Figure 3.12 (left). This shape has the minimum path length and maximum performance in the tested set, and most closely resembles the archetypical structure seen in nature (see Figure 3.1).

Configuration	Average Total Path Length
Constructal	10.9
Serpentine	25.26
Parallel	8.01
Leaf	6.5

Table 3.7: Results of the Path Length Calculations.

Comparison of Models

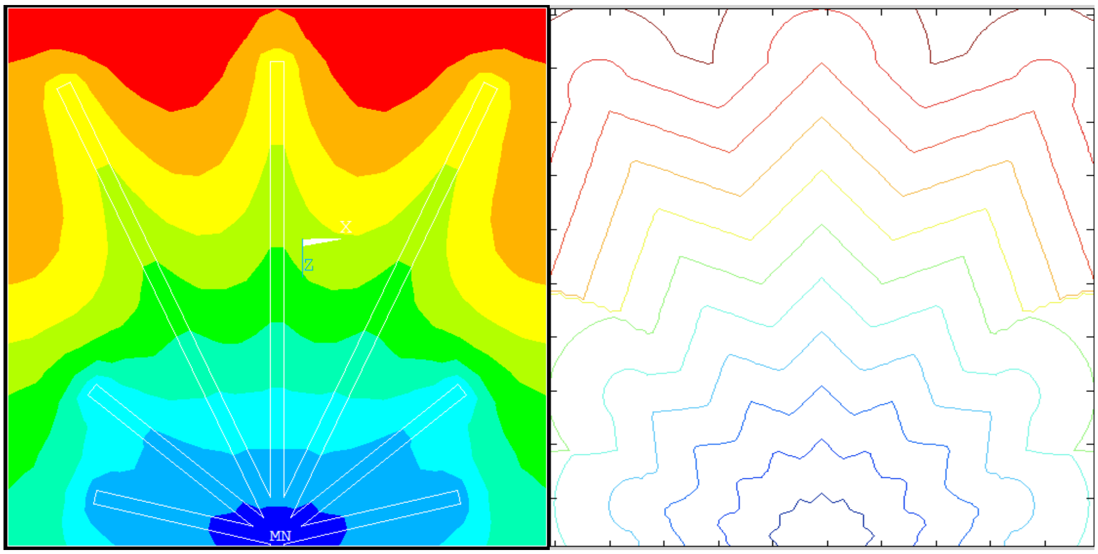
Results from the path length calculation (Table 3.7) correspond directly to cooling performance predicted by FEM (Table 3.5). The analyses show that the geometry with the shortest average total path length also has the best cooling performance for the range of values in the parametric study. For example, the leaf configuration has a near minimum average path length and the best cooling performance across the full range of modeling conditions where K2 > K1. In fact, the sequence of increasing path lengths (Leaf, Parallel, Constructal, Serpentine) corresponds exactly with the sequence of increasing maximum temperatures.

The thermal gradient vector plots in Figure 3.12 help demonstrate that the flow of heat is in fact occurring in the manner predicted by the path length analysis procedure. Heat flows first towards the channel and then along the channel towards the sink. Table 3.7 (a summary of Tables 3.4 and 3.5) shows that both methods find the same order of performance.

3.6 Discussion

In this chapter a geometric method for analyzing the performance of a cooling channel is introduced as a form of relaxed requirement virtual prototype. The purpose of this method is to simplify analysis so that more of the design space of cooling channel configurations can be explored using fewer computational resources. The agreement between FEM simulations and the more basic and simpler path length analysis is exceptional, across a very broad range of physical parameters. These results support the effectiveness of hybrid prototyping methods.

A visual comparison between the computational thermal model and the path length results is shown in Figure 3.13. This figure shows that the correlation in performance between computational heat transfer analysis and path length analysis is in fact due to a fundamental similarity between the two models. On the left is the temperature contour plot of the computational model. On the right is the contour plot of path length for each point. As expected, those points with higher path length (red-brown) color correlate to points with higher temperature (brown-red). This diagram shows the very close agreement between these two contours, and thus between the two models. A mathematical analysis of this overlay was also performed. The correlation coefficient (r^2 value) of the one-to-one mapping for each point over the entire geometry is 0.95.



a. b.

Figure 3.13: a) Leaf, FEM heat contour plot. b) Leaf, average total path length contour plot. Detailed comparison of path length and temperature. For all figures, blue is a low value, and red is a high value- with the color spectrum representing intermediate values.

3.7 Limitations

The analysis techniques discussed in this chapter have limitations. The metric of path length is applicable to heat transfer applications where length is the dominant characteristic in the equation for thermal resistance. This condition holds for many interesting heat transfer problems such as the cooling of a micro-chip [244]. The finite element analyses are based on assumptions of adiabatic wall conditions and constant sink temperature. The adiabatic condition is based on reasonable assumptions. Although no system is truly adiabatic, there will be negligible heat transfer into the walls if the chip is coated, or if the plate represents a cell surrounded by other cells. It is possible that there may be some non-linear behavior at the sink. However, two observations lead to the conclusion that the modeling technique is satisfactory: (1) the temperature distribution morphology of a plate configuration was found to be independent of the sink point temperature, and (2) the sink condition is consistent across the configurations so that the comparison between them is objective. A final limitation is that only four configurations are analyzed. Other geometries and conditions should be explored, where path length analysis may be used to estimate preferred choices for more detailed analysis. However, the geometries in this study represent some of the major cooling channel designs found in the literature and are geometrically diverse.

3.8 CONCLUSIONS

This research examines a new analysis technique for the volume-to-point transport problem for the specific example of cooling a microchip using biological analogy as a source of inspiration. The goals of this research are (1) to introduce a novel metric to evaluate volume-to-point flow systems; (2) to posit, through the example of a design procedure that has cooling channels that mimic a leaf, that the implications of this metric can be leveraged as a design tool; and (3) to determine if leaf-like shapes are more efficient than other analyzed geometries for the given problem. Each of these goals has successfully been addressed by the analyses presented in the chapter.

To achieve these ends, a multi-pronged research approach was employed. The path length metric (i.e., the average transport distance from the heat generation points to the sink through both the substrate and then along the channel) is used to evaluate the performance of several cooling channel designs. The performance of these designs is also evaluated using finite element analysis. The results of these two approaches are strongly correlated, and suggest that the path length metric can be used to evaluate a channel configuration's cooling performance, at least as an estimating tool to explore varied channel configuration design spaces. Interestingly, the leaf-like channels have a qualitatively natural appearance that is highly analogous to the veins of a biological leaf, thereby affirming the biological analogy.

Chapter 4: A Systematic Method for Design Prototyping[2]

OPENING REMARKS

This chapter pursues development of a systematic method to guide application of individual or hybrid techniques as part of an overall prototyping strategy in which many individual prototypes may be produced. The contributions of this chapter include a deeper review of several key individual techniques. The empirical data on these techniques is then synthesized into key heuristics. Further experimental studies are reported to compare the effects of these individual techniques. A systematic method for developing a prototyping strategy is also presented. It is based on direct application of the key heuristics. Finally, prototyping performance outcome is compared between a control group and an experimental group which has been exposed to the method. The method is correlated, through experimental investigation, with increased application of these best practices and improved design performance outcomes. These observations hold across various design problems studied. This method is novel in providing a systematic approach to prototyping.

4.1 INTRODUCTION

Background

Sensitivity analysis of product development cycles shows that experimental prototyping plays a key role in determining outcome [5]. In this context, prototyping is the systematic development and testing of a new product design concept to establish its

2 B. Camburn, B. Dunlap, T. Gurjar, C. Hamon, M. Green, D. Jensen, et al., "A Systematic Method for Design Prototyping," Journal of Mechanical Design, 2015.

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feasibility and enhance detailed design of pre-production models. It has also been empirically validated that different approaches to prototyping can have a significant impact on both short- and long-term outcomes [114]. Yet, prototyping efforts are typically *ad-hoc* and implemented through the experiential base of the developer. There is an inconsistent success rate in product development [5]. Planning tools are needed to help manage the uncertainty in these processes. Therefore, it is critical to pursue research on systematic approaches to prototyping [154]. Several individual techniques to plan prototyping efforts have been proposed [1, 10, 84]. However, clarification and empirical testing of these techniques must continue so that successful outcomes are more likely and reproducible [47].

Drezner identifies of a broad range of the factors in a strategic prototyping effort through a large-scale review of military technology development efforts [42]. Identified factors include testing of parallel concepts, iterative testing, cost of each prototype, fabrication process, experience of the designer, requirement specification, and use of planning. Drezner also offers empirical evidence, including the observation that prototyping efforts in later stages of the overall product development process will incur larger costs. This list of practices is expanded by Viswanathan, in an extended review to identify practical means of implementing prototypes and benefits thereof [6]. Moe has also proposed a methodology for factoring a prototyping effort into "partitions." The approach provides a framework to select between single and multiple iterations, single and multiple design concepts, and flexible or rigid scheduling. Moe's proposed approach was evaluated through an applied case study and met with positive feedback [10]. Christie expands on this work further to identify additional guidelines, in the form of a directed list of prompts to encourage consideration of these techniques in a prototyping effort. This list includes the choice between physical or virtual prototypes as well as others [84].

Other valuable research insights include identification of some general success factors in prototyping. Yang observed that prototypes with fewer parts are more successful [58]. Jang conducted empirical studies to find that successful teams employed physical prototypes more often and hand-written notes less often. Jang's study also identified that prototyping later in the design process was associated with lower performance [34]. Häggman confirms this observation: early prototyping leads to a higher rate of success [283]. In a general sense, early prototyping occurs in the first half of a design phase and late prototyping in the second half. Additionally, Viswanathan experimentally reports that reduced time spent on each individual prototype actually correlates with improved design outcomes [72]. There are also studies of prototype use in ideation [284], exploring fixation [70], and analogy use [273]. These studies indicate the potential to strategically allocate prototyping resources early and often in the design process, but also warn about factors that will facilitate and inhibit this allocation.

While there have been many studies investigating specific aspects of the prototyping process and their connections to successful product development (as detailed above), there is not a widely applicable and accepted method for determining prototyping strategies that assists designers in making a variety of prototyping decisions. Such a method is proposed based on synthesizing identified best practice, with the intent of improving the likelihood of success of a product's development. The method is tested in a number of experimental scenarios. Thus, the motivation of this research is to provide systematic means to improve prototyping outcomes in a scientifically repeatable way. Within the scope of this work prototyping is considered for the purpose of concept development and functional testing. This particular work will not explore the relationships between early stage prototyping as used in concept development (ideation) or later stage prototypes such as those for pre-production testing. Furthermore, this work is oriented towards product design in the electro-mechanical domain.

Research Motivation and Approach

As outlined in the introduction, there is a need for the development and critical evaluation of strategic prototyping methods. This work, in particular, explores a process to develop prototypes that meet measurable design requirements with higher repeatability than a traditional, *ad hoc* approach. This process should also ideally meet these requirements with less expenditure of time and resources. To achieve this goal, several research hypotheses are formulated to guide the research effort:

1. Prototyping techniques, taking into account studied prototyping principles, correlate with successful design outcomes.
2. These techniques can be induced in designers' activities through exposure to a developed design method.
3. Use of this method correlates positively with direct measures of prototype performance.

To evaluate the first research hypothesis, a literature review is employed to discover techniques for prototyping that are correlated with success. The results of various studies are synthesized into heuristics that provide an understanding of best practices. The heuristics form the basis of a strategic prototyping method. This method, and the heuristics, are evaluated via experimentation. Research hypotheses two and three are likewise addressed through experimentation. Relevant data are collected during each experiment so that the three research hypotheses can be tested directly. This approach is outlined in Figure 4.1. This work represents the expansion and new analyses and synthesis of information shown in previous works by the authors [26, 27, 30, 82].

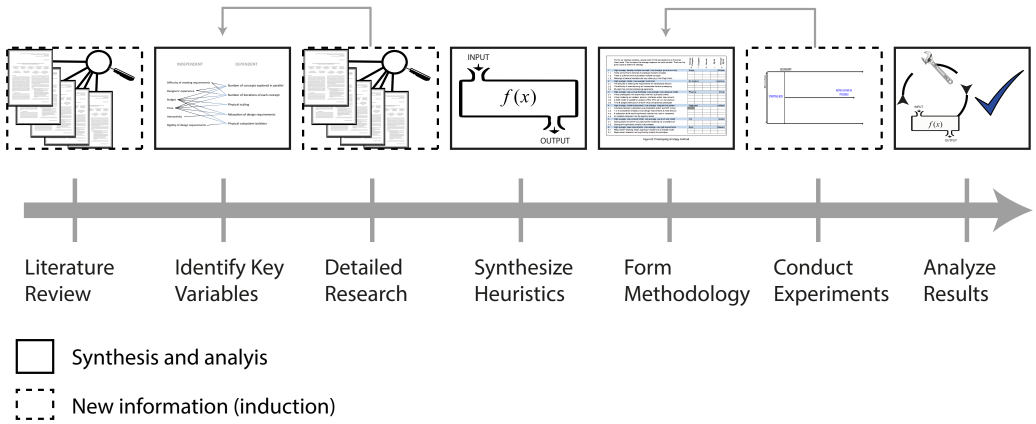

Figure 4.1: Representation of overall research method employed in this study.

Identification of Heuristics and Formation of Method

To generalize the concept of prototyping best practices, the term *individual technique* is introduced and the term *prototyping strategy* is adapted from Drezner. *Individual techniques* provide a means of enhancing the prototyping process. However, the applicability of each individual technique is dependent on context. There is also possibility for variable implementation of the individual techniques (e.g. 1:100 scale, versus 1:5 scale). A *prototyping strategy* represents the specific plan for implementing prototyping across a product development effort [42]. A planned approach consisting of a combination of choices for applying several individual techniques can be used in the formation of a prototyping strategy. For example, there is a range of possible sizes or scales for a prototype. There is also a range in the potential number of times a prototype may be improved or altered and then iteratively rebuilt and tested. This section reports key findings from the literature, exploring empirically validated best practices in detail. This literature has been critically synthesized to form heuristics that describe best practices, which in turn form the basis for a systematic prototyping method. Discussion of the synthesis process and presentation of the method itself follows at the end of the section. A set of variables that quantify the individual techniques, as well as identified metrics of performance, are listed in Table 4.1. Iterative and parallel prototyping are intended to directly lead to improved performance. Scaling, subsystem isolation, and requirement relaxation are complementary techniques, intended to reduce cost and time expenditure. Thus multiple concepts and iterative testing can be a viable avenue, even in cases of limited time and budget. Furthermore, as the literature has shown that faster prototyping can reduce fixation [72], these techniques could potentially lead to more novel concepts as well.

Specific Process Variables	number of iterations
	number of parallel concepts
	use of scaling
	use of subsystem isolation
	use of requirement relaxation
	use of virtual prototypes
Outcome Assessments	performance of each prototype
	time to build each prototype
	cost of each prototype
	adherence to suggested approach

Table 4.1: Metrics, both for process and outcome.

Iteration

In this context, iteration is defined as the cycle of building, testing, and improving as applied to a single design concept. A basic, small-scale illustration of this concept is the iterative design of a novel conveyor belt geometry to reduce stress and improve performance (Fig. 4.2). In another example, Drezner oversaw a US Department of Defense (DoD) study reviewing full-scale projects that included prototypes for complex designs, such as helicopters and autonomous aircraft systems. This study identifies that prototypes can be used in build-test cycles to systematically advance towards a mature design [42]. Glegg suggests product development projects are best served by a progression of three design iterations: the base idea, the first embodiment and the contemporary embodiment [285]. Ulrich identifies that a firm has the choice of developing prototypes sequentially or in parallel with different cost, benefit, and time implications. The number of iterations may be given by the timeline divided by the expected duration of the prototyping cycle [285].

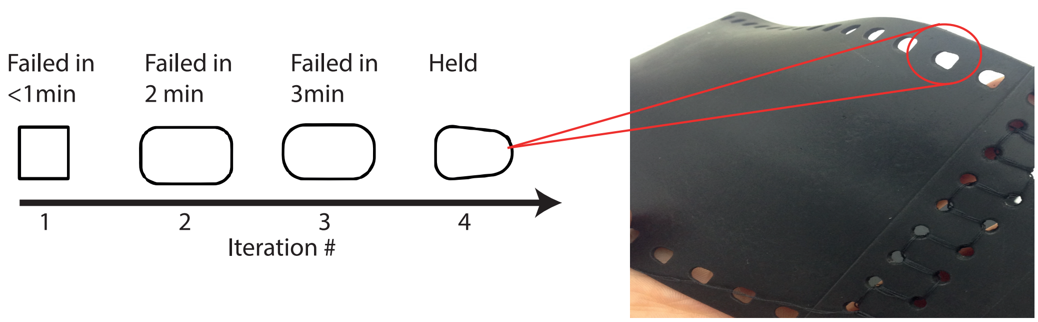

Figure 4.2: Use of iteration in design for spoke holes on a conveyor belt: (left) schematics of four tested design generations, and (right) image of the final design. Through iteration, performance was increased to an acceptable threshold.

Thomke observed, from an industry case study, that there is a difference in the number of iterations designers apply depending on the fabrication tools employed. For two different fabrication processes, differing patterns in iteration were observed. For programmable circuits, an average of 13.90 iterations were made, but for hardwired application-specific circuits only 1.49 were employed [114]. Notably, Thomke explores the effects of cost on iteration from a theoretical perspective [85]. Viswanathan confirms the relationship between method and speed of iteration, noting that teams given a less complex fabrication process produced more iterations, and more prototypes overall than an equivalent group with a more complex or more time intensive fabrication process [72].

Dow also experimentally validated that iteration improves performance. Teams in one group were required to pursue at least three design iterations, within an equal timeframe to a second group that produced only one. The iteration group achieved a significant increase in performance for a design task compared to the control group [113]. In summary, the research highlights that exploring multiple iterations is significantly beneficial depending on the factors of sufficient time and other resources (materials/funding/personnel).

Parallel Concepts

The exploration of parallel design concepts is defined as the fabrication and testing of two or more diverse or fundamentally different core design concepts to achieve the same function or affordance properties during one product development project. For example, the design of an inverted pyramidal structure to prototype prostheses can benefit from examination of several concepts in parallel (Fig. 4.3). Badri identifies, from an industry study, that multiple research teams working concurrently enhance the design outcome [5]. Ulrich notes that typically, a firm has a choice of developing prototypes sequentially or in parallel with different cost, benefit, and time implications [113]. Riek adds that the total number of prototypes may be given by the size of the budget divided by the expected prototyping cost. In an industry case, the design team built three designs in parallel, each with apparently equal potential. This permitted exploration of the design space in the limited amount of time available [154]. Thomke finds that industry projects typically explored many design concepts in parallel. However, he notes that integration of the information produced by each effort is critical and may not always occur [122]. The implication is that co-operative, rather than competitive, parallel prototyping, mitigates this problem (which the method applies).

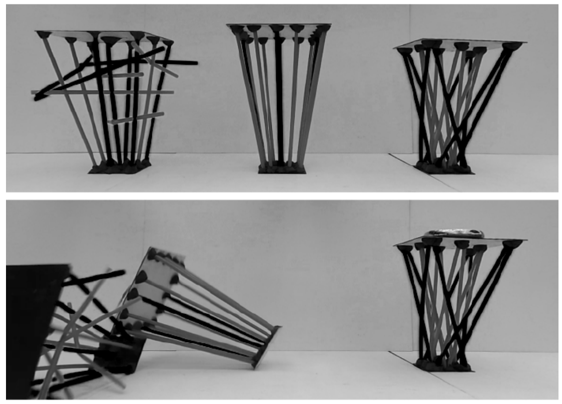

Figure 4.3: Use of parallel prototyping for strut design in a prosthetic limb: (top row) three concepts before load is applied; (bottom row) three concepts after load is applied. Parallel testing highlights differences in performance; clearly only one concept (right) held the load.

Additional insight in this area is provided by Dahan and Mendelson, who derive a modeling equation to provide a guide for the number of concepts to pursue in parallel [115]. Moe summarizes these observations in a prescriptive approach as follows: the number of concepts pursued in parallel can be proportional to the current available budget [10]. Christie also observes that although only one or two concepts are likely to be finalized, developing multiple prototypes at an early stage can help provide critical design feedback [84].

Dow experimentally validates that pursuit of multiple concepts enhances performance in advertising design. In a study, two groups of designers developed ads for a website. The experimental group was required to present several concepts at each of their design reviews. The other teams presented only a single concept at each review. The experimental group achieved much higher success rates, on average 264 ad-clicks, while the control group received only 158 ad-clicks [117]. Neeley confirms that pursuit of multiple concepts also increases performance for physical product design. Teams in an experimental group were instructed to design up to five concepts for a tower, while teams in the control group produced only one with otherwise equal conditions. While only about 34 percent of teams completed all five concepts, the experimental teams reached a tower height of 40.53 inches on average. This was greater than the control teams, which reached 31.55 inches on average, with statistical significance [119]. This research indicates that parallel concepts can significantly improve performance, improve concept evolution, assist in making decisions between multiple concepts under uncertainty, and reduce errors in a design.

Scaling

A scaled prototype, in this context, is one that has been physically reduced or increased in size while retaining the original proportions and relationships (scaling laws) between components and the underlying working principles of the system. For example, in the design of a chamber for contained fluid flow, a significant amount of material cost and time were saved to validate system interfaces with a scaled model (Fig. 4.4). Moe proposes several open design questions regarding the potential of scaled designs. However, strategic prototyping methods are required to identify the conditions for these choices [10]. Viswanathan provides observations from an *in situ* study of designers. When scaling a model, loads and related boundary conditions should also be scaled accordingly [6]. This condition is most often accomplished through the use of dimensionless parameter groups, scaling laws, or mappings of performance parameters across functional testing [101, 106, 109, 110]. Christie provides further scenarios for the use of scaled models, such as ships or aircraft, where creation of a full size prototype for testing may not be feasible prior to manufacture [84].

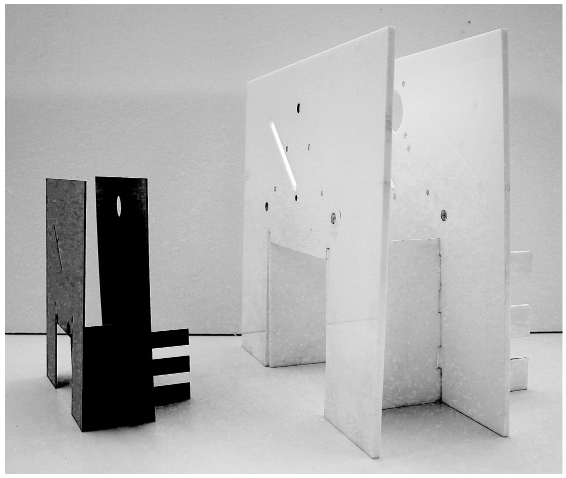

Figure 4.4: Use of scaling in design of a fluid flow chamber: (left) scaled model, and (right) full size model. Use of a scaled model saved time and material during tests of system interfaces.

Cho explores the capability of similitude methods (based on the use of dimensionless groupings as mentioned previously). Similitude is a property shared between a physical system and a model which has been engineered to mimic the real system via scaled parameters for testing. He also introduces an advanced technique of empirical similitude that involves multiple parallel models, each scaled with respect to one aspect of the final system. For instance, the first model may be constructed with the correct geometry but made from basic materials, while the second model is made from the final materials but constructed with a simpler geometry. Traditional similitude models reach about 97% predictive fidelity, while empirical similitude models can attain more than 99% [110]. These sources highlight that scaled models can reduce costs on complex designs and still return valuable design insights.

Subsystem Isolation

Subsystem isolation, in this context, refers to a prototype that models the performance and function of a single subsystem in isolation, rather than a full design concept. For example, it might save effort to produce one or two components and test the design of a joint without producing the entire system (Fig. 4.5). Christie notes that prototypes can be of a single subsystem, of a set of subsystems, or of the entire system. When prototyping a large or complex system, it may be beneficial to break the effort down into smaller subsystems that can each be approached with an optimal local strategy for the corresponding components. Depending on the interfaces, this approach may allow for easier testing of prototypes. However, effective re-integration is critical. This technique can be especially effective when one subsystem of an existing product is being evolved but the remainder of the system remains unchanged or has only small changes [84].

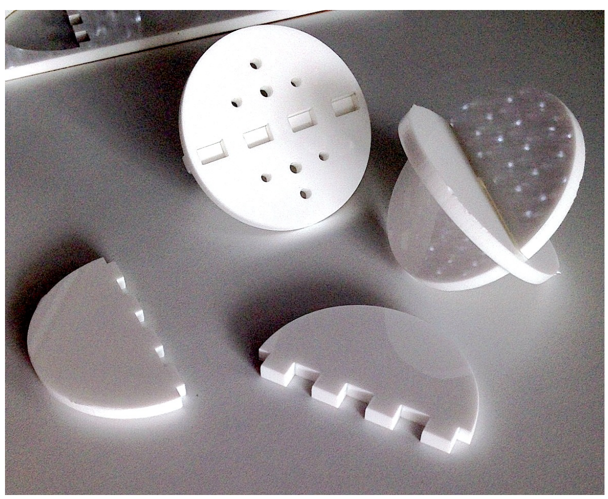

Figure 4.5: Use of subsystem isolation in design of a joint. Several joint concepts are pictured. These isolated prototypes were significantly easier to test without encumbrance of the full system.

Drezner elaborates through an experimental case study that some defense systems are generally too costly to prototype at the system level (e.g., large naval surface vessels or complex satellites). In such systems, subsystem isolation is a cost-effective approach to reducing uncertainty [42]. For example, a naval project for a destroyer class vessel successfully used a series of critical subsystem prototypes, including elements such as the hull form, advanced gun and its munitions, composite deck house, peripheral vertical launch missile system, and radars, among others, to reduce technical risk and refine each subsystem's design [42]. This experience and results from a similar study of a United States Air Force program suggest that under appropriate conditions, useful testing data might be obtained for about 60 percent of the cost of a fully integrated prototype [42]. This approach also reduces time to market. These and other sources show that subsystem isolation can reduce complexity and allow productive exploration of a subsystem at lower cost than a full system model.

Requirement Relaxation

Relaxation of requirements indicates that a prototype will operate to meet some (perhaps a reduced) percentage of the initial functional requirements. This may mean that other requirements are not tested at all (for a given prototype) or that the intention for such a prototype may be to meet certain requirements only partially. For example, an acrylic box meant to withstand substantial forces might first be prototyped in cardboard to examine the size of the box and joint design (Fig. 4.6). Relaxed requirement prototypes are a subset of low fidelity prototypes in that the functional requirements are reduced, or a subset of requirements is addressed. Low fidelity prototyping is a more general form of relaxation in which any aspect(s) of the design could be relaxed. Drezner observes that prototypes are used to demonstrate critical attributes of the final product in a realistic environment. However, the prototype should focus specifically on those informational aspects about which there is the most uncertainty [42]. Christie elaborates that the early prototypes should achieve threshold (as opposed to objective/final) design requirements. These threshold requirements will likely be tailored to each specific subsystem. This approach also permits earlier stage results. Therefore, for a prototype, each requirement should be specifically defined *a priori* according to the needs of the problem or scenario to ensure effort and resources are not wasted [84].

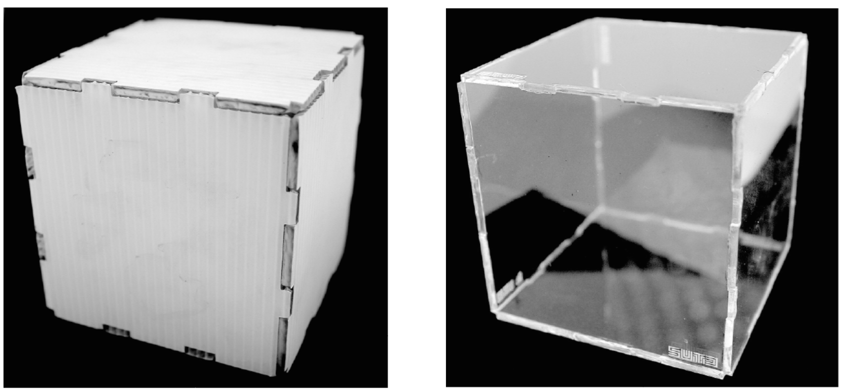

Figure 4.6: Use of requirement relaxation in design of an acrylic box: (left) cardboard relaxed requirement prototype, and (right) full prototype. The cardboard model took significantly less time and budget to produce but gave valuable design insights.

Thomke and Bell explore analytical models based on the value added through testing. In essence, each test reduces some uncertainty in design performance, and removes a subsequent cost of resolving errors arising from that uncertainty. These models identify that significant savings can be achieved through multiple low fidelity prototypes. Furthermore, it is found that tests with partial fidelity are beneficial when multiple low cost designs are evaluated [85]. This result should be highlighted in synthesis with the observation that low fidelity prototypes reduce cost to permit faster prototyping [42], and that faster prototyping reduces design fixation [72]. This research indicates that requirement relaxation, a subset of low fidelity prototyping, is a viable approach to reduce costs and provide useful information during design development.

Virtual Prototyping

A virtual prototype evaluates some aspect of the real-world behavior of a design via simulation on a computational platform [131]. Virtual prototyping is typically implemented through the use of analytical models, computer-based simulation, and visualization techniques. A prototyping effort may involve both physical and virtual models. For example, the design of a Baja vehicle may at different times include both physical and virtual design prototypes before full implementation (Fig. 4.7). Ulrich and Eppinger propose that a designer select either virtual or physical prototypes by attempting to reduce effort and increase modeling accuracy. Specifically, the ratio of accuracy of the model to effort of construction is used to guide the choice. This is essentially a recommendation for the approach that is easier and more accurate [285]. Two key benefits of virtual prototyping are reducing effort in cases where physical testing is prohibitively expensive [93], and in providing data which would be infeasible to collect from a physical model due to geometric constraints [128].

Clin demonstrates the versatility and uniqueness of virtual prototypes for complex and highly customized situations, such as developing braces to treat spinal deformities in scoliosis [131]. Goldstein also provides an example design scenario in which virtual models can be created within hours for complex 3D objects that would otherwise take weeks to physically embody [146]. In some cases, it should be noted that production of a physical model might be faster. Wang expounds that one of the greatest benefits of virtual prototyping is the possibility of synthesizing design with testing [286]. Wen details that virtual models are critical for finite element analysis. Such analyses can be correlated to field test data for validation, and then the models can be expanded to help to identify weak structural elements that would normally only surface with full life use [129]. Christie proposes that the implementation of prototypes as either physical or virtual should be a strategic one. Since computers have enabled reduced effort for complex calculations, CAD models can translate into reduced cost or enhanced accuracy. However, designers note that there are limitations to the virtual approach. Virtual models require a substantial time expenditure on interaction with the tool interface [41]. The outcome may be critically dependent on the selection of parameters which will be modeled [152]. Since a virtual model is based only on phenomena which are incorporated in the model, if a physical phenomenon is relevant to the behavior of the real world design, but not included in the virtual model, there is no way the virtual solution can include those effects [152]. An example would be not including aerodynamics in the model of a chassis, but only accelerations due to nonlinearities in the road.

Figure 4.7: Use of virtual and physical prototypes in Baja vehicle design: (left) virtual prototype, (center) physical prototype, and (right) final prototype. The virtual prototype permitted a rapid system overview and permitted iteration with reduced effort.

Sefelin evaluated the use of physical and virtual prototypes in a controlled experiment. Participants designed both a touch screen system and a novel calendar. The results indicate that performance was about 15% higher for the virtual prototyping condition, but the results were not statistically significantly. In accord with this finding, exit interviews confirmed that most designers preferred the flexibility and reduced effort of the virtual models [93]. The research indicates that for certain design problems, virtual prototypes can save cost and provide novel information (such as large perturbation studies) that are not feasible to acquire with physical models.

Outcome Assessments

The first three outcome assessments: performance, time to build each prototype, and cost of each prototype are used based on the precedence of previous literature. Performance, i.e., the degree of meeting design requirements, is a direct measure of the success of the projects. Time, i.e., person-hours spent on fabrication or blueprint design, and cost, i.e., budget spent in dollars, are metrics which may be direct if there are requirements of such for the project. Time and cost also help to evaluate the prototyping process. Finally, adherence to the suggested approach (from the method) is a self-reported measure of how closely a participant observed their team to utilize the method or if instead a different approach was chosen. Adherence to the suggested approach is used to compare how closely use of the method is connected to increase or decrease of the other metrics.

Summarized Heuristics and Systematic Method

The observations from the literature were critically evaluated and combined to develop a set of conditions to guide when and to what extent each of the techniques has a high potential to positively influence the design process. Iteration and parallel concept testing directly improve performance, while virtual prototypes, scaling, subsystem isolation, and requirement relaxation can permit reduction of cost and time expenditures without loss of performance. These latter four techniques are critical because they may enable iteration and parallel concept testing, even in situations of constrained budget and time. See Table 4.2.

Individual Technique	**When to apply**
Test Multiple Iterations	The problem is difficult relative to experience, e.g., uncertainty is high
Explore Parallel Concepts	Material, budget and time resources permit multiple concepts Ideation has produced multiple promising concepts
Scale the Prototype	Scaling laws permit construction of an accurate model Scaling appears likely to save cost and time
Isolate a Subsystem	Interfaces are predictable There is a critical subsystem Building the critical subsystem will save time An isolated system will provide useful information
Relax Design Requirements	Requirement relaxation will permit valuable information gain Requirement relaxation appears likely to save cost and time
Use a Virtual Prototype	A virtual prototype will permit valuable information gain A virtual prototype appears likely to save cost and time Time permits later construction of a physical prototype

Table 4.2: A summary of key heuristics.

Figure 4.8 represents the simplified systematic method. The method is a systematic tool that can be used as a source of guidance for design in the development of a prototyping strategy. The method synthesizes these best practices; however, there are potentially a number of different ways to do this. Other format options might include flowcharts, equations, or prompts to guide team discussion, etc.; the key is to provide designers with a basic approach for considering and evaluating key insights of the literature findings. The method expands beyond the traditional view of a stage-gate process with a ‘proof of concept’, then ‘alpha’ and ‘beta’ level prototypes to include a large potential ‘prototyping space’, defined by six independent variables that represent independent techniques. The method is a translation of the empirical evidence found in the literature into a form that can be applied in general to a design problem. This method combines the available theoretical information for each of the six key techniques. Each of which has a potentially variable application. This information is presented to the designer as several questions that each require a Likert scale response. The average of these sub-question scores then provides a single value, used to indicate a suggested approach.

Technique	Context Variable	Heuristic	Assessment Disagree Strongly -2	Disagree -1	Neutral 0	Agree 1	Agree Strongly 2
Iteration	(performance)	There is potential for significant performance increase					
	(fabrication)	A fabrication method can be chosen that will permit iteration.					
	(resources)	The expected cost of iteration is relatively small compared to the total budget.					
	(time)	The expected time to iterate is relatively small to the total project timeline					
	average the above	Low average: pursue one only. <--> High average: pursue several iterations.					
Parallel Concepts	(resources)	There are sufficient resources to prototype multiple concepts.					
	(time)	There is sufficient time to prototype multiple concepts.					
	(ranking)	Rankings of several concepts are very close (e.g. from Pugh chart).					
	average the above	Low average: pursue one only. <--> High average: develop multiple concepts.					
Scaling	(models)	Scaling law(s) will permit accurate system modeling via a scaled build.					
	(feasibility)	Scaling will significantly increase the feasibility of prototyping.					
	average the above	Low average: use a full size model. <--> High average: use a scaled model.					
Subsystem Isolation	(interfaces)	Interfaces between subsystems are predictable and re-integrable.					
	(requirements)	1 or 2 subsystems embody the critical design requirements.					
	(resources)	Testing a subsystem would substantially reduce expense of resources					
	(testing)	Testing of an isolated subsystem will validate a key function					
	average the above	Low average: integrate the system. <--> High average: isolate subsystems.					
Requirement Relaxation	(requirements)	The requirements require refinement					
	(concept)	At this stage, concept development is the most critical					
	(resources)	A reduced requirement prototype will significantly reduce resource usage.					
	(usage)	At this stage it is important to simulate usage scenarios					
	average the above	Low average: use rigid requirements. <--> High average: relax requirements.					
Virtual Prototypes	(effort)	Virtual prototype(s) will reduce effort compared to a physical one(s).					
	(availability)	The required tools to develop a virtual model are available					
	(data)	A vritual model will provide accurate test data					
	(design)	A virtual model will facilitate other needs: complex topology, integrated testing					
	average the above	Low average: use a physical model. <--> High average: use a virtual prototype.					

Figure 4.8: Survey tool for implementation of prototyping method. See Appendix for full page version

Each individual technique is given a full question in the survey tool. To determine the suggested approach for an individual technique, the designer answers each Likert prompt under a heading then takes the average of those scores. The average of the Likert score is then mapped onto the given scale, which provides a unique approach for each technique. Note there is a relevant magnitude which indicates the degree to which that approach is likely to benefit the process. When a neutral response is identified, the designer must reconsider the questions until an indication towards either approach is given. This combination of multiple prompts allows for competing elements of the design context to be weighed against each other and still permit a clear plan for each technique. From the method there are 4^6 implementable unique strategies that could be indicated. This approach saves significant time over memorizing and attempting to individually weigh all of the information identified in the literature review. Typically, the method is presented by providing examples as shown in Figure 4.2 through 4.7, and then the method in Figure 4.8 is provided to the designers. The method provides guidelines for implementing each individual technique, where the combination of these techniques constitutes a suggested approach. The suggested approach is then translated into the context of a specific problem as a complete prototyping strategy through the efforts of the designer. This concept tends toward a dimensionally enhanced approach as compared to the traditional strategy of achieving stage gate objectives in sequence (from alpha level to beta level prototyping, etc.).

Case Studies: Prototyping Efforts

The method (as shown in Figure 4.8) guides application of each technique. Execution of a complete strategy can become complex. Two case studies are reviewed in which strategic prototyping was applied. The first case is the architectural renovation of a historic structure in Beijing. The second is a pre-commercial product from SUTD.

A large scale renovation project is currently underway in Beijing. The firm executing this renovation has asked that details of the project remain anonymous until the project is complete; however, their strategy can be discussed. Production of a full scale prototype is impossible in this case for two reasons. First, it would exceed the budget of the project. Second, it is too dangerous to risk damaging the original structure. To address these issues, a more systematic strategy was adopted. For concept selection, several parallel, relaxed requirement prototypes were compared. The final concept is a synthesis of these parallel-developed concepts.

Prototyping for the final concept was segmented into two isolated subsystems. The first was a virtual model representing the full system, including the original structure as well as the enhancements. It is a four dimensional model that represents dynamic (electronic) surfaces that will be installed over the existing structure, in a virtual environment. The environment can be navigated. It also simulates external inputs such as sunlight. This full-scale, virtual, simulation was iteratively developed. Simultaneously, a series of full scale, physical, parallel subsystem prototypes were pursued. Production material samples were used to prototype each interface. For example, a single tile of the holographic flooring was fit to the stone wall. This isolated interface prototyping provides precision to the detailed virtual simulation. This strategy permitted detailed prototyping of the design with reduced risk. For example, subsystem isolation was critical because of the delicate and critical nature of interfaces with the original structure.

Considering a second case, Idea cube is a hand held three dimensional white board in a pre-commercial product development phase at SUTD. It can be used for concept sketching or for representational drawing of objects. The cost of prototyping this design at full scale is a fraction of the project budget. However, the initial prototype was produced with relaxed requirements to save time and explore functionality. Next, the project was split into three isolated subsystem prototyping efforts. First is the whiteboard cube. It was iteratively refined over several full scale, full requirement prototypes. Various aspects of durability were tested. Several features such as ruled edges, and a sliding hinge were also added to this subsystem. The second isolated subsystem was a small sculpture that fits inside the cube to demonstrate the impact of viewing angle. At first, four different concepts for the sculpture were prototyped in parallel at full scale, with relaxed requirements. A form inspired by Escher's 'impossible staircase' was selected. This concept was iterated several times, with non-relaxed requirements. Over the iterations, varying aspects of geometry and material selection were refined. The third subsystem was a custom packaging, iteratively developed from lasercut cardboard. The dimensions of the cube were set to enable isolated simultaneous development of the sculpture, cube and packaging. This approach was driven by the strategy method, for instance, iteration was recommended because of the relatively low cost per test.

4.2 Experimental Exploration and Validation

To investigate the proposed method and its elements, it was necessary to construct several complementary experiments. These experiments were each designed in a similar manner with variations in type of design requirements and length of study to permit a rich understanding of the effects of the method. This section details each of the experiments that were constructed to test the research hypotheses. There were three shorter-term, design challenge type experiments, and one long-term *in-situ* study. Multiple design problems were explored. This experimental approach reduces the potential that results could be skewed by the selection of a particular design problem. A high-level, contrasting overview of the unique objective for each study is presented in Table 4.3. Particularly the binary and controlled performance measure studies permit a clear quantification of performance effects, while the in-class study provides a deeper view of cost and time expenditure factors for the scaling, subsystem isolation, and requirement relaxation strategies. The following section details objectives, data recording techniques, metrics, design problems, participants, time allotments, and material allotments for each study. Note that there were no repeat participants between any of the four experiments. Also, for each study, participants consisted of a random mixture of male and female junior and senior university students majoring in either mechanical engineering or industrial design. The number of participants varies slightly due to the fact that participation was on a voluntary basis for each study.

Title	Unique Objective
Study 1 - Binary Design Objective	Explore a problem with strict pass/fail or 'binary' measure of performance
Study 2 - Open Design Objective	Explore a problem where there is no practical upper limit on design performance
Study 3 - Virtual Prototyping	Explore a problem for which either physical or virtual prototypes appear applicable
Study 4 - Capstone Design	Explore a context in which the prototyping efforts occur over an extended period

Table 4.3: Overview of Studies.

Study 1 - Binary Design Objective

In the first two controlled studies, an experimental group was exposed to the method, while a control group was left to develop their own approach to prototyping (as typically occurs in most design contexts). The first study evaluated impact of the method on performance for a ‘binary’ design requirement. That is, this requirement simply had a pass/fail condition. This generally mimics binary (hard) design requirements. For this study, a researcher observing each team measured and recorded the performance distance, in this case using a caliper. The participants kept a log of their iterations and concept testing. The metrics and conditions are listed in Table 4.4.

Measured:	Conditions:
• Performance • Number of Iterations • Number of Concepts	• Experimental: Method • Control: No-method

Table 4.4: Metrics and conditions of Study 1 - Binary design objective.

For the first controlled study, teams were asked to build a device that starts within a bounded area on the floor and then moves a given object, a US quarter-dollar coin, to cover a target. It was required to stay within bounds and operate using the system’s stored energy (i.e., teams could not push the device to actuate, rather they were required to pull a release pin). Figures 4.9 and 4.10 illustrate the problem. There were 15 minutes for introduction of the problem, followed by 30 minutes for method instruction (experimental group) or free ideation (control), then there were 180 minutes for building. Each team was supplied with the following materials in a pre-made kit: cardboard, rubber bands, paper clips, paper, cardboard, foam, CDs (compact discs), pencils, pipe cleaner, PVC pipe, masking tape, box cutter, scissors, marker. There were 36 participants in this study, equally divided between experimental and control groups. Participants completed the design problem in teams of two persons [82].

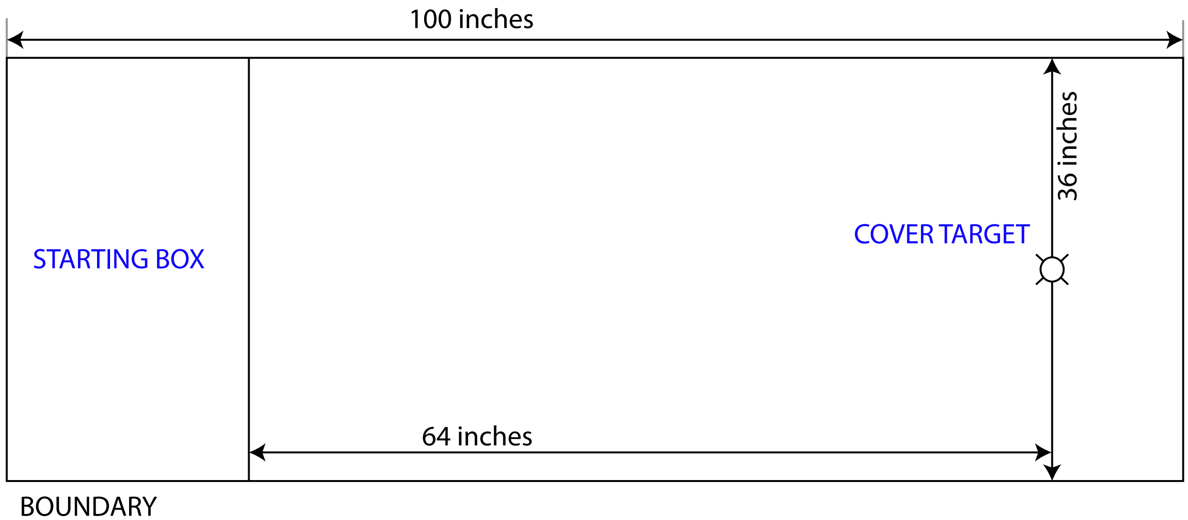

Figure 4.9 Depiction of design problem for Study 1 - Binary design objective.

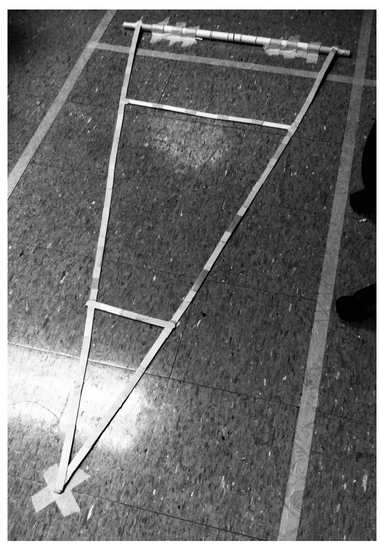

Figure 4.10: Example prototype from Study 1 - Binary design objective. This design acts like a drawbridge - dropping the coin into place.

Study 2 - Open Design Objective

The second controlled study evaluated the impact of the method on an open-ended design performance requirement. This requirement had no theoretical limit on performance. This generally relates to variable (soft) type design requirements. For this study, a researcher observing each team recorded the performance of each iteration (in this case distance, determined by tape measure), changes made, and time of testing. The metrics and conditions are listed in Table 4.5.

Measured:	Conditions:
• Build Time (each iteration) • Performance (each iteration) • Number of Concepts • Number of Iterations	• Experimental: Method • Control: No-method

Table 4.5: Metrics and conditions of Study 2 - Open design objective.

The second controlled study is complementary to the first, with the only difference that teams were required to move an object, a piece of paper, as far as possible down a hallway. Again, the device was required to start within a bounded box, operate using stored energy, and not pass over the sidelines. Figures 4.11 and 4.12 show this experiment. The problem introduction was 15 minutes long, followed by 5 minutes for method instruction (experimental group) or free ideation (control); there were then 50 minutes for building. Each team was supplied with the following materials in a pre-made kit: cardboard, rubber bands, paper clips, paper, cardboard, foam, CDs (compact discs), pencils, pipe cleaner, masking tape, box cutter, scissors, marker. There were 64 participants in this study, equally divided between experimental and control groups. Participants completed the design problem in teams of two persons [27].

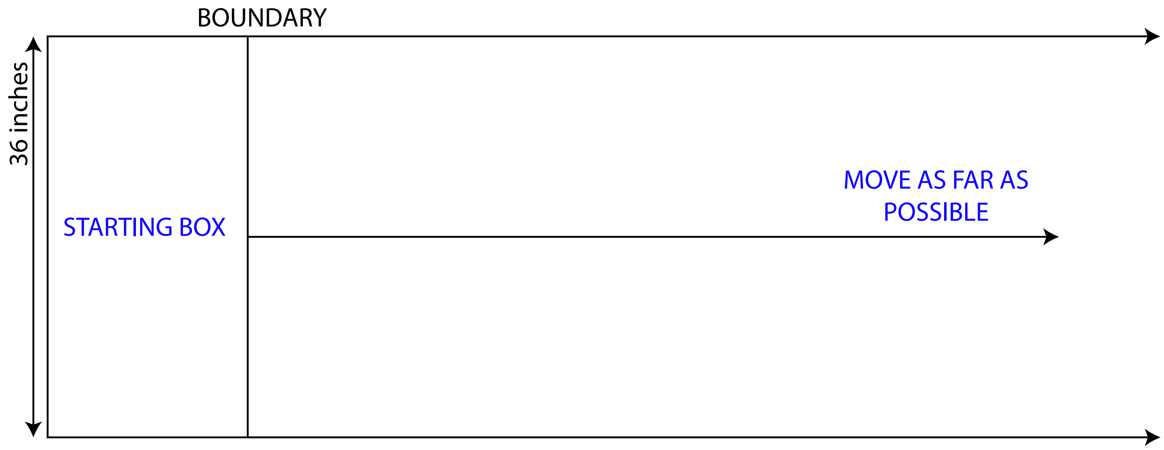

Figure 4.11: Depiction of design problem for Study 2 - Open design objective.

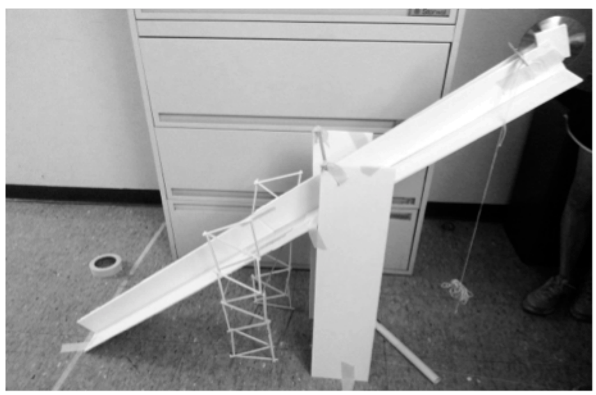

Figure 4.12: Example prototype from Study 2 - Open design objective. This design acts like a ramp, guiding a disc into a rolling motion along the track.

Study 3 - Virtual Prototyping

The third controlled study evaluated differences between physical and virtual prototypes. Some design problems are impractical to solve solely with virtual or physical modeling respectively. However, the objectives of this study were to evaluate performance differences for a problem that could readily be solved by either, and whether the method encourages virtual prototyping or not. For this study, a researcher observing each team recorded the time to complete the design. The researcher also measured and recorded performance of the physical prototypes, while the virtual prototype performance was extracted by the researcher from the simulation software. Participants were provided with the method and were allowed to subsequently choose physical or virtual prototyping but not both. The metrics and conditions are listed in Table 4.6.

Measured:	Conditions:
• Build Time (until finish) • Performance (final design)	• Selection of Physical • Selection of Virtual

Table 4.6: Metrics and conditions of Study 3 - Virtual prototyping.

In this third controlled study, participants were required to design a four-bar linkage that traces a path. The design performance metric for this problem was the ratio of horizontal (x) motion to vertical (y) motion. The primary objective was to obtain the highest ratio in the allotted time. Figures 4.13 and 4.14 provide details. Individuals were introduced to the design problem for 15 minutes, then given the design method and allowed to choose between virtual or physical prototyping. Individuals were separated according to their selection and given a 5 minute introduction to either the physical prototyping tools or the linkage design software. Each participant was provided with either a computer terminal and access to the linkage simulator for virtual prototyping, or a hole punch, scissors, plastic rivets, cardboard and pencil for physical prototyping. Then all participants were given up to 50 minutes to prototype. There were 32 participants in this study. Each participant completed the design problem individually [30].

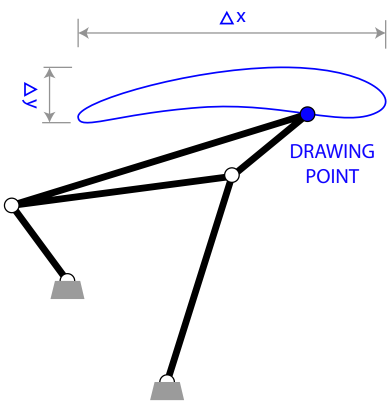

Figure 4.13: Depiction of design problem for Study 3 - Virtual prototyping.

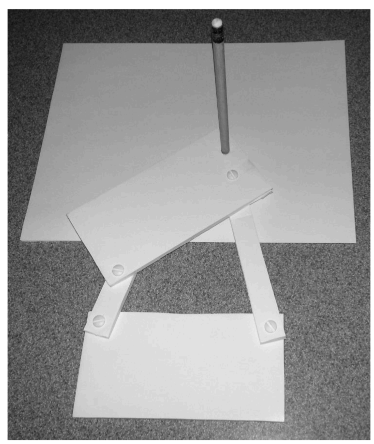

Figure 4.14: Example prototype from Study 3 - Virtual prototyping. This physical prototype traces the pencil in a desired pattern on the sheet of paper.

Study 4 - Capstone Design

This study consisted of providing the method to students in a senior mechanical engineering capstone design course. The objective of the in-class study was to evaluate the impact of the method and use of the various approaches supported by the method. In particular scaling, subsystem isolation, requirement relaxation, and physical or virtual prototypes were implemented in full for this experiment. Many of the projects in this course are industry sponsored and teams often produce high-end custom fabricated prototypes. This permitted deeper exploration of the approach taken by participants, as well as the observation of additional quantitative information such as the cost of each prototype. For this study, researchers conducted individual interviews with each team to collect data. Two researchers worked with the teams while they completed an evaluation of the cost of each prototype (in US dollars), the time to produce each prototype (in hours), and the team-perceived performance of each prototype and value of information gained from each prototype. The metrics are listed in Table 4.7.

Measured: • Performance of Each Prototype • Use of Scaling, Subsystem Isolation, Requirement Relaxation, and Virtual Prototyping • Cost of Each Prototype • Time to Construct Each Prototype • Adherence to Suggested Approach • Number of Prototypes Constructed

Table 4.7: Metrics and conditions of Study 4 - Capstone design.

For the in-class study, each team was matched with an industry or research sponsor and provided a unique design problem. These ranged from development of sealing valves for offshore mining rigs to prototypes for medical equipment. This was an advantage in that it also permitted validation of the methodology for a broad segment of the design problem space, thus reducing any potential influence due to a specific problem. At the beginning of the semester, two researchers introduced the methodology through a lecture and provided the survey tool. The teams then had 3 months to build various prototypes. The researchers returned to conduct interviews at the end of the semester with each team, to assess their prototyping effort. Figure 4.15 shows an example. There were 105 participants in this study. Participants completed their design projects in teams of 3 to 5.

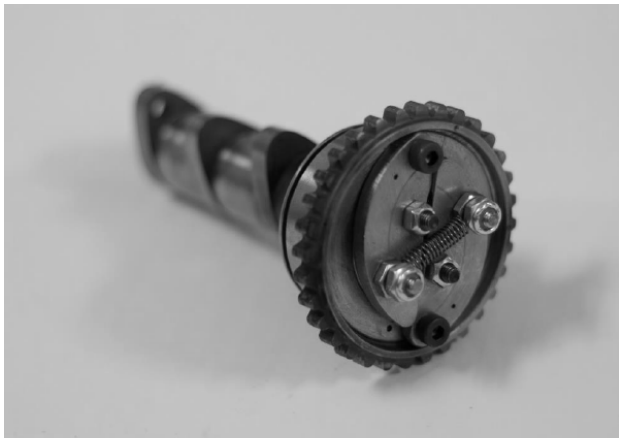

Figure 4.15: An example prototype from the capstone design study, a cam phaser.

4.3 Results and Discussion

This section reports results from all four experiments. For convenience, the results section is mapped to the research hypotheses. Data pertinent to each hypothesis are presented in sequence. The pursuit of several experiments permits each research hypothesis to be evaluated. This section is organized to first report results of the influence of each individual technique on performance; this relates to the first research hypothesis. Next, results relating to the second hypothesis regarding increased use of the techniques with exposure to the method is evaluated. Finally, results pertaining to the third research hypothesis are presented, regarding effects of the method on overall design performance. It is observed that each of the individual techniques can have a positive impact on design outcome. These results are reported with a new level of detailed quantification. Furthermore, the method increases use of the individual techniques and improves overall performance.

Throughout this section, both the Student's *t*-test and the test of two proportions are employed. The Student's *t*-test is applied for hypothesis testing in cases where a performance measure and thus resulting difference of means can take on variable values. For the purposes of this work, it is assumed that any value for p less than 0.05 will suffice to reject the null hypothesis with statistical significance for the Student's *t*-test. Secondly, for instances in which there is a binomial distribution (only two possible values) the results are analyzed using the comparison of two populations' defective proportion. This test uses a transformed *z*-test to test the hypothesis that two samples are from the same population. For the purposes of this work, it is assumed that any value for p less than 0.05 will suffice to reject the null hypothesis with statistical significance for the test of two populations' defective proportion.

Hypothesis 1: Individual Techniques Improve Outcome

Iteration

The influence of iteration on design performance was measured in the variable performance controlled study. The literature indicates that iteration improves performance [72, 113]. This correlation was observed here also. The open-ended nature of this problem allows for quantification of the marginal effects of iterations, which are reported here for the first time (Fig. 4.16). Repeated tests without design changes are excluded. Performance continues to increase with many iterations. The performance value can increase to 400% of the initial test performance. Another way of looking at this result is that on average, each iteration provides a 12% increase in performance. The r^2 value is 0.85 for mapping the results to the line equation of gradient 12%, and intercept at 19 feet (computed average for initial performance).

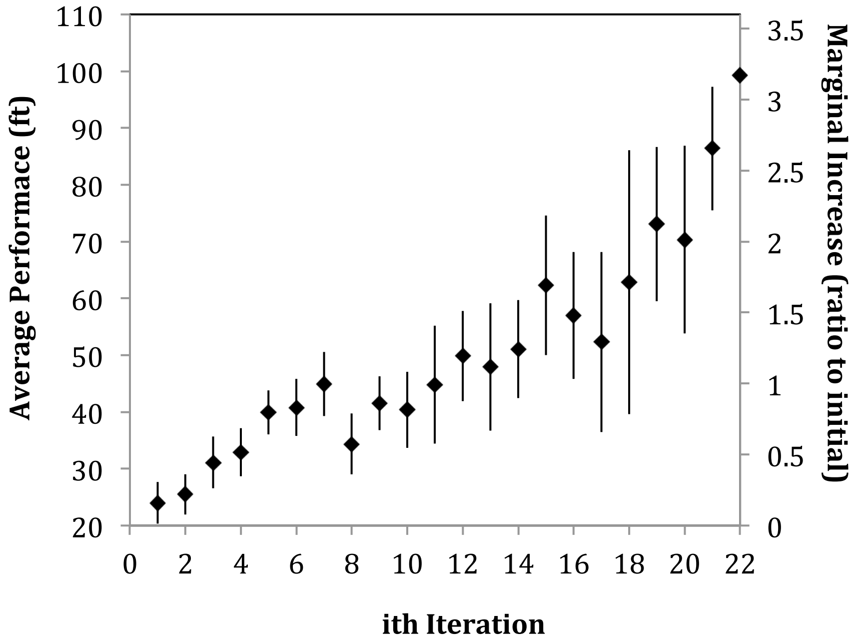

Figure 4.16: Performance with respect to increasing number of cycles of iteration. ±1 standard error shown. Source: Study 2 - Open design objective. Each point represents the average performance of the i^{th} iteration, across all teams.

In remarkable complement to the increase in performance observed with iteration is the decreasing cost of execution in terms of time to complete each iteration (Fig. 4.17). The first build takes significantly more time than subsequent, evolutionary builds. Furthermore, there is also a general trend of decreasing time to build each i^{th} iteration. There are some outliers at higher numbers of iteration, thus large standard error at these points. From experimental observations, these were instances where a prototype failed and required significant repair time. Another way of looking at these results is that the time to build each iteration decreases by about 8% for each iteration (excluding the initial build).

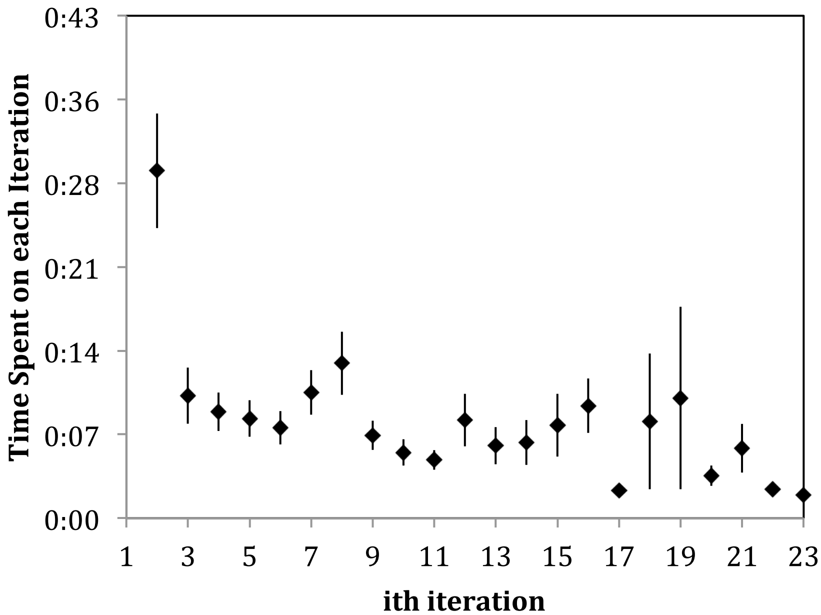

Figure 4.17: Time spent to develop each iteration with respect to i^{th} iteration. ±1 standard error shown. Source: Study 2 - Open design objective.

Parallel Concepts

As would be expected from the existing literature [117, 119], exploration of a second concept was also correlated with a performance increase beyond the first concept. Figure 4.18 shows that the average performance of a team's second concept is higher than their first. This was significant with Student's *t*-test at $p < 0.001$.

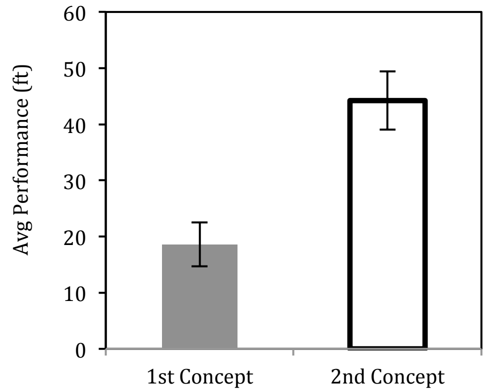

Figure 4.18: Average performance for first and second concept within each team. ±1 standard error shown. Source: Study 2 - Open design objective.

Interaction of Iteration and Parallel Tests

Several interesting results were found in terms of comparing iteration and parallel concept development, from analyzing results of Study 2 - Open design objective. This study permits some basic comparative evaluation of these two techniques as the performance metric is a continuous. On average, teams which included an additional concept introduced it on the 3rd iteration. Furthermore, the average score for the first two iterations in teams that attempted two or more concepts (19 ft.) was significantly lower than the average scores of the first two iterations for those that only iterated (29 ft.). This difference was significant with a Student's t-test at p = 0.05. One possible interpretation of this result is that the teams chose to explore a second concept after observing that the first concept was not working well.

Although the second concept typically performed much better relative to the first, in this study, there was no statistically significant difference in final performance between teams purely iterating and those developing multiple concepts (across all teams). One explanation for this finding is that since a large quantity of iterations was permitted (up to 30 in one case), the effects of parallel prototyping may have been less pronounced (the largest number of parallel concepts was three). The average number of total iterations was 11 whether teams tested a second concept or not (for Study 2 - Open design objective). This result indicates that teams strictly iterating improved one concept over 11 iterations while those changing concepts only produced on average 8 iterations of the second concept; which might also account for the outcome.

In the experiments, exposure to the method has been controlled; however, teams are given freedom of choice in pursuing a prototyping strategy, where the objective is to simulate as realistic a design experience as possible. Based on the distributed usage of iteration and parallel testing, the experiment is fractional factorial. Main effects are reported in the preceding section.

In terms of time expenditure, the first iteration of the second concept only took an average of 12 minutes to fabricate. This time duration is significantly less than the time required to produce the first iteration of the first concept (30 minutes). This difference is statistically significant at $p = 0.04$. This result is intriguing in that it suggests that as participants build the first concept they may be learning the tools and design problem more deeply, so that development of a new concept does not take much more time than an additional iteration of one concept.

One final, practical observation is that even during development of a single concept, some teams implemented isolated subsystem development in parallel. For example, one member might be developing the base, while the other develops the projectile. In this sense, there are even ‘mixed’ forms of iteration and parallel prototyping.

Scaling

The results for scaling, subsystem isolation and requirement relaxation were collected from the in-class study. To evaluate the main effects of scaling, subsystem isolation, and requirement relaxation, single factor ANOVA and pairwise Student's *t*-tests are employed. Participants were interviewed and completed a form detailing performance and value of information on a ten point Likert scale, and cost and time spent as dollars and hours respectively for each prototype built in the experiment. For scaling, as would be expected from the literature [101, 106, 109, 110], there was a reduction in the cost to produce each prototype. Scaled prototypes cost teams significantly less than full-size physical prototypes with $p = 0.003$. There was also a reduction in time to build each prototype, but not quite significantly so, at $p = 0.058$. There was no significant difference in performance of scaled prototypes. However, there was a significant *increase* in the value of information gained, at $p = 0.039$ for the *t*-test that scaled models afford more useful information (Fig. 4.19).

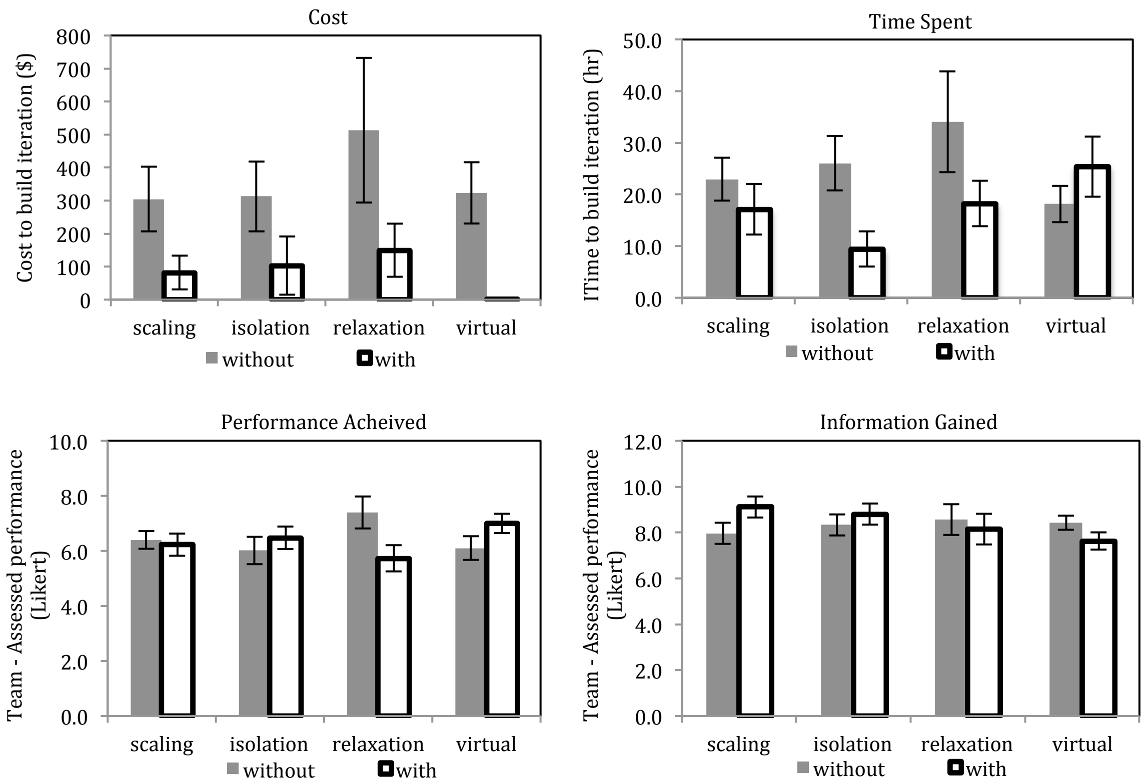

Figure 4.19: Four metrics to evaluate prototypes with regards to scaling, subsystem isolation, and requirement relaxation. ±1 standard error shown. Results are for each prototype on average in class study with regards to: (top left) cost expended, (top right) time spent, (bottom left) performance achieved, (bottom right) information gained. Source: Study 4 - Capstone design.

Subsystem Isolation

The mean cost and time to produce prototypes of an isolated subsystem were less than that of producing a full system. However, these differences were not quite significant (Student's *t*-test at $p = 0.07$ for each). There was not any significant reduction in performance or information gained (*t*-test values are $p = 0.40$ and $p = 0.255$, respectively). Only a small percentage of prototypes were produced as isolated subsystems; thus, there were not enough data points for statistical significance (Fig.

4.19). However, based on the trends of the other results, it appears that with more data points these differences would likely become significant.

Requirement Relaxation

For requirement relaxation, there was an expected significant savings in cost (Student's *t*-test, $p = 0.01$) and time (Student's *t*-test, $p < 0.001$) to produce a prototype as compared to prototypes constructed without requirement relaxation. There was no significant difference in the information gained with relaxed prototypes. As would be supported by the literature [42], however, there was a significant reduction in performance of these prototypes (*t*-test $p = 0.009$). This is exactly what is expected for relaxed requirement prototypes, as it is intended that the saved time and cost will offset the performance. The final performance of teams that pursued at least one prototype with a relaxed requirement was slightly higher on average than those that only pursued full scale prototypes, but not significantly so (*t*-test value is $p = 0.16$). This approach allows for additional iterations or more budget allocation to the final prototype (Fig. 4.19).

The possibility of testing for interaction effects between scaling, subsystem isolation, and requirement relaxation was also evaluated. In Study 4 - Capstone design, the teams were free to ultimately choose their own strategy, after exposure to the method. As a result of this freedom of choice, some of the factor trials for an ideal 2^3 factorial experiment are not present which would be required to evaluate a bilinear (or greater order) regression model of the interaction effects of these three techniques. For instance, there were no cases of scaling without requirement relaxation. Thus, the experiment is equivalent to a fractional factorial approach. The significant main effects have been identified and reported in the preceding section.

Virtual Prototyping

There was a large reduction in cost observed with virtual modeling compared to physical modeling observed in Study 4 - Capstone design. This result was significant for the Student's *t*-test at $p = 0.005$. It is important to note for this result that modeling software was already available to the teams. In some cases modeling software may not be available and would require purchase. There was no reported difference in time required to build prototypes for each iteration. There was a significant increase in performance at $p = 0.009$ for the Student's *t*-test (Fig. 19). There was a small increase in value of information gained for virtual prototyping but not significantly so, at *t*-test $p = 0.061$.

For Study 3 - Virtual prototyping, the task was to design a four-bar linkage to produce the highest ratio of horizontal to vertical travel within a cycle. Figure 4.20 and Figure 4.21 show the results of this assessment. There was a significant increase in performance for participants who chose to pursue a virtual prototype, as well as a reduction in time to finish. Of course, the results of this study are highly dependent on the specific design problem being addressed.

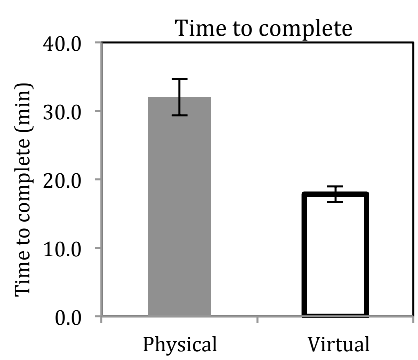

Figure 4.20: Time to complete the target task and surpass a minimum ratio of 5:1 in the controlled linkage study. ±1 standard error shown. Source: Study 3 - Virtual prototyping.

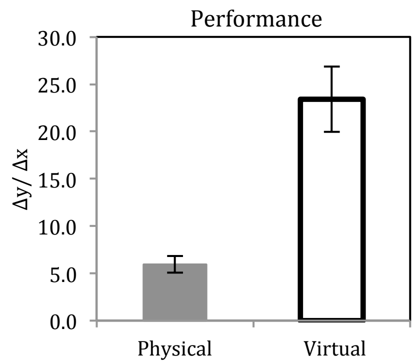

Figure 4.21: Performance as ratio of lateral to vertical distance achieved with linkage design at the end of the prototyping session in the controlled linkage study. ±1 standard error shown. Source: Source: Study 3 - Virtual prototyping.

Hypothesis 2: Use of Individual Techniques Increases with Exposure to Method

This section reviews whether participating designers applied the techniques more often when exposed to the method. The next section will evaluate impact on outcome.

Regarding the use of iteration, Figure 4.22 shows that the experimental teams iterated more than the control teams during Study 2 - Open design objective. The difference of means was significant using Student's *t*-test with $p = 0.006$. On average, the experimental teams iterated on their design concepts 13 times while the control group only iterated 9.3 times. Teams in Study 1 - Binary design objective also pursued more iterations on average: 6.1 for experimental versus 3.7 for control, also significant at $p < 0.001$ for Student's *t*-test.

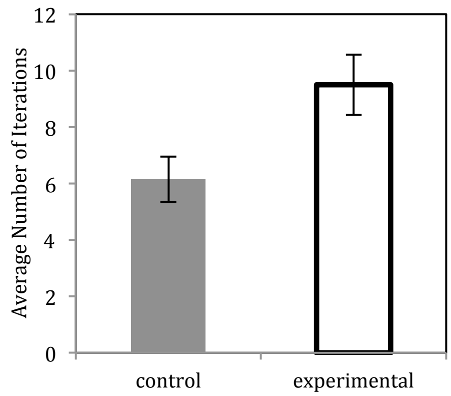

Figure 4.22: Average number of iterations on original concept observed in each condition. ±1 standard error shown. Source: combined results of Study 1 - Binary design objective, and Study 2 - Open design objective.

When comparing the number of concepts developed in parallel by the experimental and control groups, it was observed that the average number of concepts pursued per team was higher in the experimental group for the variable performance, Study 2 - Open design objective. This difference was significant with the Student's *t*-test at $p = 0.005$. Figure 4.23 shows the average number of concepts pursued per team. Teams in the experimental group of Study 1 - Binary design objective also pursued more concepts: 3.2 on average versus 1.6 in control, which was significant for Student's *t*-test with $p < 0.001$. This result is seen as a positive result as the literature identifies that pursuing multiple design concepts in parallel prototypes is correlated with increased performance [117, 287].

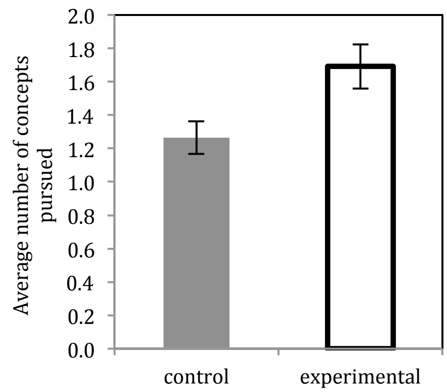

Figure 4.23: Average number of concepts pursued control versus experimental groups. ±1 standard error shown. Source: Study 2 - Open design objective.

For scaling, from Study 4 - Capstone design, there was a significant observation that teams adhering to the method (high Likert-scale response, i.e. '4' or '5') used scaled prototypes more often than those that diverged (low Likert-scale response, i.e. '1' or '2'), with $p = 0.04$ for test of two populations' defective proportions. It was noted that significantly more teams used subsystem isolation when they adhered to the suggested approach, but still less often than they employed other techniques like scaling. Similarly, significantly more teams used requirement relaxation when they adhered to the suggested approach. Finally, it was observed that teams adhering to the suggested approach applied virtual prototyping more often than those that diverge from the method. Additionally, Study 3 - Virtual prototyping also indicates that significantly more individuals select virtual prototypes when presented with the method. From the total set of participants, only 9 individuals selected to pursue physical and 23 individuals selected virtual prototypes (test of two proportions, $p < 0.001$). See Table 4.8.

Adherence to Method Likert scores: 1, 2 = diverged 3 = neutral or N/A 4, 5 = adhered	% Prototypes Scaling	% Prototypes Subsystem Isolation	% Prototypes Requirement Relaxation	% Prototypes Virtual
Adherence scores 1, 2	33%	0%	50%	43%
Adherence scores 4, 5	54%	48%	86%	77%
Test of Proportions *p value*	**0.0427**	**0.0001**	**0.0278**	**0.0176**

Table 4.8: Use of scaling, subsystem isolation, requirement relaxation and virtual prototypes with respect to adherence to the suggested approach for Study 4 - Capstone design. Note that those adhering to the method used these practices significantly more often. Source: Study 4 - Capstone design.

Hypothesis 3: Use of the Method Improves Outcome

Overall, observations indicate that teams exposed to the method started prototyping sooner. This result is seen as a positive result as reducing time to begin testing of the first prototype has been correlated with success in the previous research [34, 58]. Figure 4.24 shows that the mean time passed from the start of the prototyping session to test of the first prototype was only 19 minutes for the experimental group, which was 22 minutes faster than the control group for Study 3 - Virtual prototyping. In other words, the experimental group produced prototypes in less than half the time it took the control group. This difference is statistically significant at $p = 0.01$, Student's t-test. Time to first test was also faster for experimental groups in Study 2 - Open design objective.

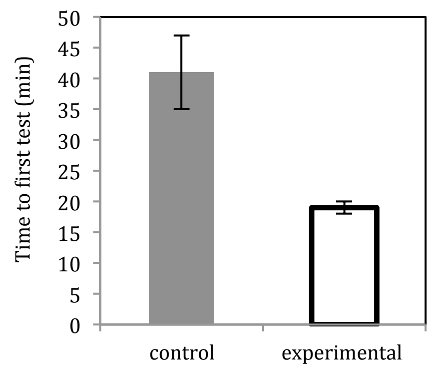

Figure 4.24: Time to start in the controlled study. ±1 standard error shown. Note that the experimental teams started testing in roughly half the time it took control teams. Source: Study 2 - Open design objective.

In terms of direct performance measure outcomes, the experimental teams also outperformed the control teams in both of the controlled experiments that allowed this comparison. For Study 1 - Binary design objective, where teams were required to 'cover a target', all of the experimental teams met the target requirement while only 56% of the control teams met the target performance. This percentage is the raw percent of teams that were able to build a device to move a quarter to cover the target 'X', under its own power, and within the allotted time (Fig. 4.25). This difference in percentages is significant using the test of two proportions at $p = 0.0044$.

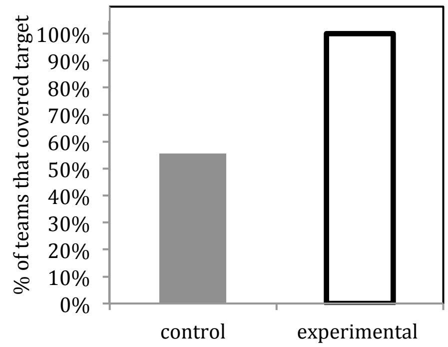

Figure 4.25: Raw percentage of teams able to cover the target within the allotted time. Note that all experimental teams completed the goal. Source: Study 1 - Binary design objective.

There was also a significant difference between the experimental and control groups for Study 2 - Open design objective. This challenge was to move an object as far as possible (Fig. 26). On average, the experimental teams moved the object 50 feet, while the control teams moved the object 41 feet. This difference is significant using Student's t-test at $p = 0.018$.

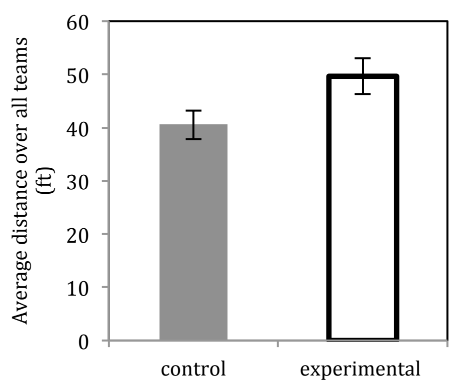

Figure 4.26: Mean distance each team propelled the supplied object. ±1 standard error shown. Note that the experimental teams moved the object 9 ft. farther than control, on average. Source: Study 2 - Open design objective.

For Study 4 - Capstone design, it was observed that there was a correlation between adherence to the method and prototype performance. Each team addressed a unique design problem. This is advantageous, as it permits the method to be evaluated in a broad range of design problems. However, each team has different relevant performance metrics. Therefore, general metrics were used for Study 4 - Capstone design. Each team was asked several questions, including: (1) "How closely did your team follow the method?" and (2) "What was the outcome performance of your prototyping efforts?" The results in Figure 4.27 highlight that performance was directly proportional to how closely teams adhered to the approach suggested by the method, for their specific problem. The difference between close adherence ('4' or '5', on Likert scale) and low adherence ('1' or '2', on Likert scale) was significant for Student's *t*-test at $p < 0.001$. These problems were also much longer term than the controlled problems.

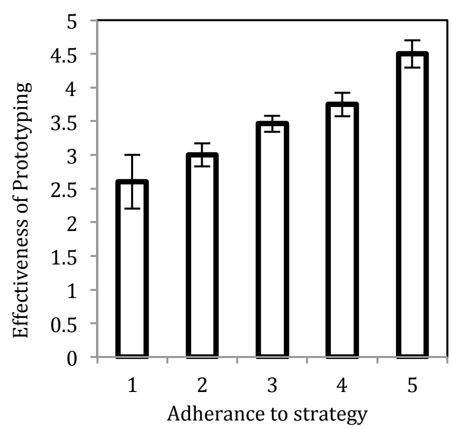

Figure 4.27: Comparison of how closely teams followed their suggested approach, and outcome performance of prototyping efforts. ±1 standard error shown. Source: Study 4 - Capstone design.

4.4 CONCLUSIONS

Regarding the first research hypothesis, "*Prototyping techniques, taking into account studied prototyping principles, correlate with successful design outcomes,*" an extensive literature review was conducted and six key individual techniques were identified. For each of these techniques, there was substantial empirical literature that identified a 'best practice' approach to its implementation. In addition to the literature findings, several effects of these techniques on the prototyping process were also experimentally evaluated.

In Study 2 - Open design objective, it was observed that iteration and multiple design concepts improved design performance significantly. Specifically, for the first time, the quantitative value of continued iteration has been reported. It was observed that performance continued to increase with multiple iterations, even to the point of a 400% performance increase at the 20th iteration on average; and notably, the time expenditure of each test is decreased with increasing iterations.

From Study 4 - Capstone design, it was observed that the use of scaling and requirement relaxation significantly reduced the cost of a prototype as well as the time to construct it. For requirement relaxation, there was a slight decrease in performance of that prototype, as would be expected from the literature [17, 42, 85], since by definition a relaxed prototype requires less rigorous performance; however, this had no significant effect on final performance. Subsystem isolation was also correlated with reduced time and cost, but not significantly so, as fewer instances of this were pursued comparatively. Virtual prototyping was correlated with drastically reduced prototyping costs. For scaling and virtual prototyping, there was no significant loss of performance. Performance actually increased for virtual prototypes.

A controlled experiment, Study 3 - Virtual prototyping, also confirms and expands these results about virtual prototyping. Participants designed a linkage in this study. Individuals employing virtual prototyping achieved higher performance, and also produced their final design in less time than those using physical prototypes. These individuals reported that virtual prototypes “required less unnecessary effort” than physical ones for the problem. The particular design problem of this study is well suited for both physical and virtual models; however, in some cases either may be infeasible and there is not a need to choose between the two.

Regarding the second research hypothesis, “*These practices can be induced in designers’ activities through exposure to a developed design method”,* these best practices were reformulated as heuristics and finally translated into a general methodology. Next, this method was introduced to designers in several controlled design studies as well as an in-situ experiment. The results of these studies indicate with statistical significance that each of the six key techniques were applied more often in the experimental groups that were exposed to the method in the controlled studies. Additionally, for Study 4 - Capstone design, it was observed that teams which reported adhering to the suggested approach also applied each of the individual techniques more often than those that reported diverging from the method. This refers to adherence to the approach suggested through completion of the survey tool.

Regarding the third research hypothesis, “*Use of the method correlates positively with direct measures of success”,* teams exposed to the method achieved greater final design performance than control groups with the same material and time allotments. This was observed for Study 1 - Binary design objective, as well as Study 2 - Open design objective. Teams also started prototyping significantly sooner in the experimental group. It was also observed for Study 4 - Capstone design that teams adhering to the method performed better than teams which diverged from the method. The approaches of scaling, subsystem isolation, and requirement relaxation work in concert with the benefit of iteration and parallel concept exploration. Scaling, subsystem isolation, and requirement relaxation approaches drastically reduce the time and cost to develop each prototype. Furthermore, pursuit of parallel concepts, as well as iteration, significantly improves performance. Thus, the simultaneous use of several of these approaches can permit the pursuit of multiple prototypes and subsequent performance enhancement, even when time and budget are limited.

Limitations to the Study

It may be argued that an empirical design study is limited by selection of the design problem. One of the challenges of design problem selection is in identifying which results are generalizable, and into what other contexts. One possible approach to address this issue is to explore several unique problems and contexts. In this work, several different and complementary design problems were evaluated in multiple, parallel controlled studies. In a fourth, in-class study, participants of this study addressed a large variety of design problems. This in-class study also occurred over a longer term. Comparable effects were observed between Studies 1-3, and Study 4 - Capstone design. Further, the results regarding each of the individual techniques match what would be expected from the literature. The literature includes results drawn from analysis of full-scale industry projects. A remaining challenge is to quantify to what limit, in terms of design context, the results are generalizable.

The research studies only address six techniques while there may in fact be a large number of other valuable techniques. However, the literature identifies these techniques as critical with significant empirical support. By forming a method from strategies that are well founded on empirical results from the literature, chances are increased for success and potential value. This approach matches well with the results that indicate performance increase associated with the method. Although it was possible to identify the marginal benefits of iteration, it would be equally interesting to explore the marginal benefits for additional concepts in parallel. For the current work it was difficult to encourage teams to produce more than two designs and too few teams explored three or more concepts to return statistically significant results. Additionally, it would be valuable to develop a more strategic method for guiding integration of subsystems. The current method does not provide any specific guidelines for which system to isolate, or how to later integrate it. Finally, detailed implementation of the requirement relaxation technique is also left to the designer. It would be ideal to also develop specific approaches to defining how to relax a requirement and to what degree.

The fundamental assumption of this work is that context can be effectively evaluated to determine a suggested approach towards a prototyping strategy. In some cases the context may be somewhat vague, ambiguous or unclear. Engaging in a miscalculated retyping strategy could result in loss of time or resources. An example would be underestimating the cost of iterating on a relaxed requirement prototype and later not having enough budget to build the second iteration. Therefore the context must be carefully evaluated to ensure that an appropriate strategy is identified.

Future research

There are several interesting avenues now open for future research. It was noted in the literature review that there is significant impact on outcome with regards to the type of fabrication process employed. It is known that faster fabrication is preferable; however, there may be many techniques to achieve this. The following chapter explores additional sources of design information regarding best practices for prototype design and fabrication. In addition to the experiments described above, versions of the method have been deployed at universities and design seminars around the world, from the University of Tsinghua in Beijing, community design seminars in Papua New Guinea, to advanced coursework at the United States Air Force Academy. Feedback by participants of all backgrounds, from Air Force colonels to native entrepreneurs, indicates that the individual techniques are critical for prototyping, yet the method of transmitting this information can be further simplified. Possible variations could include simplifying the heuristics into demonstrative 'cards' with graphic examples or something more naturally integrated with the design process, such as an annotated 'prototyping notebook' for tracking and planning prototypes. Finally, there is also an opportunity to integrate this method, or analogous methods, with other processes in design. Other areas open for advancement include: examination of performance and cost effects of utilizing mixed prototypes (a mixed prototype is distinct from a virtual or physical prototype but has elements of both); evaluation of early stage strategies including exploration of prototypes for ideation and fixation reduction; or a heavily controlled study in which a full regression model could be obtained for the interaction effects of the techniques, with the caveat that such a proscribed experimental model may have other effects on the progression of an in-situ design problem.

Chapter 5: Principles of DIY Prototype Design and Fabrication: Analysis of a Crowdsourced Design Repository[3]

OPENING REMARKS

This chapter explores the relatively open prototyping design research problem of guiding design and fabrication of individual prototypes. Previous chapters provide individual and integrated techniques which can be used to achieve certain objectives related to planning prototype development, which are typically at a systems level. Specifically, this chapter investigates project articles on the open source, Do-It-Yourself (DIY) database: Instructables.com. The database consists of guides for producing low cost functional prototypes. This database is a unique repository of design data as the design process to develop the prototypes is documented along with the final build information. Through a systematic research methodology, five prototype fabrication principles are extracted from this repository. Online crowdsourced assessment enables refinement and validation of the principles. Based on the refined principles, one of two groups in a controlled study was exposed to the principles. The study evaluates connectivity, *successful adoption of the method by participants in the experimental group*, and resulting design performance. Two case studies of prototypes are also provided. Application of the principles appears to positively impact prototyping outcomes.

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3 B. A. Camburn, K. H. E. Sng, K. B. Perez, K. Otto, D. Jensen, R. Crawford, et al., "The Way Makers Prototype: Principles of DIY Design," ASME international design engineering and technology conference, draft accepted, Boston, MA, 2015.

Contributions: B. Camburn lead researcher, article author; K. Sng, K. Perez provided assistance in conducting experiments, and inter-rater testing; K. Otto, D. Jensen, R. Crawford, K. Wood provided research guidance and editing.

5.1 INTRODUCTION

Prototyping is critical to success in the early stages of design. For example, projects without a working prototype are rarely funded on the incubation platform Kickstarter.com. Empirical design research of prototyping has provided: strategic methods [10, 26, 27, 30, 82, 84, 288]; effects of timing efforts [58, 60, 63, 119, 283]; outcomes of process techniques such as iteration or parallel prototyping [117, 288]; and studies of fixation [70, 173, 289]. Existing methods [10, 26, 27, 30, 82, 84, 288] provide high level planning of the prototyping process. These recently developed methods indicate a substantial opportunity to explore systematic and strategic approaches to design and fabricate prototypes. Knowledge of means to reduce effort and improve build quality of prototypes complements existing research. What, then, are fundamental principles for successful prototype design and fabrication? One avenue for exploring this question is to review emergent do-it-yourself (DIY) design repositories. This work follows a systematic investigation of the open source database Instructables.com in order to extract principle means of prototype design and fabrication. This particular repository was chosen not only for the rich variety of entries, but also for the intense detail in which projects are described. The users who frequently generate successful content on the platform are typically professional designers and engineers from a variety of backgrounds, although electrical, industrial, and mechanical designers are most prevalent. This information can be obtained from user profiles. Numerous users also employ the site as a testing ground for launching designs which are then sent to market. This database is explored through careful article selection algorithms and repeated testing procedures. These procedures are designed to reduce noise in results from the study.

The DIY Design Movement

What is DIY design? DIY design is typically implemented outside of the framework of professional design, for the purpose of practical gain [290]. It may often be an individual activity; however, sharing communities have recently evolved [291]. Although research suggests that DIY communities are social in origin [292], there are currently numerous platforms with a high technology orientation. Information moves organically in these communities. Experts may seed forums with extensive topic knowledge [293]. This exchange can directly lead to the mutual benefit of participants [294]. In turn, a forum of creativity is emerging where open-sharing is highly valued [295]. The paradigm permits individuals a self-reliance to modify or develop certain technologies [296]. It is possible for individuals without a technical background to fabricate a cellphone, or other complex tools [297]. This movement does not eliminate the need for large-scale manufacture of basic components; however, it does act to democratize technology through information sharing [297]. The DIY development can share benefits of craft such as high quality aesthetic [298]. The opportunity is much greater than this alone however. Genuine technological advancements are within the scope of non-experts [296].

What opportunities does the DIY movement present for design research? Often in a traditional design scope, needs assessment is conducted in partial isolation from the user [299]. For DIY projects, the designer is often also the final user. Open sharing permits iterative evolution as each participant advances a design to fit their needs [300]. The development of personal fabrication also provides a novel design arena. Open source part databases (e.g. Thingiverse, Shapeways), in combination with free modeling software [301], and low cost digital manufacture (3D printers or laser cutters), make design and fabrication of geometrically complex parts a desktop activity [301].

Distributed manufacturing networks (e.g. Alibaba) provide means of accessing components and materials in low volume directly from suppliers [302]. Other platforms (e.g. Instructables, Make, Highlowtech, Reprap, Opendesk, DIYlife) provide project guidance [301]. There are companies deploying DIY centered hardware and software (e.g. Arduino, Adafruit). Labs are also experimenting with DIY, enabling hardware development, including paper mechatronic platforms [303], or haptic interface designs [166]. Open source software likewise permits algorithmic generative design, to reduce the effort of digital modeling [304]. Hacker-spaces, incubators, and online platforms exhibit creative and inquisitive design. The results of these efforts can be seen as functioning in parallel to industry and research [305]. In this framework, designer, manufacturer, supplier, and consumer act as distributed networks. There is thus an open opportunity to connect directed research with these emergent activities [306].

Design Principles Extraction

Koen identified heuristics, or principles, as fundamental to the engineering approach [21]. Other seminal works, including Pahl and Beitz' work on engineering design [307], Blessing and Chakrabarti's design research methodology [308], and Suh's axiomatic design theory [309] have also laid foundations for research in design principles. Principles provide aid in the solution of a problem, but may not directly provide a solution themselves [21]. Contextual flexibility is a property of design principles. One means of identifying principles is through categorization and classification. These are critical as mechanisms to represent large amounts of information in a compact form [22, 310]. Recent work in principles of transformable design [311] and product flexibility [312] provide near-field analogies for extracting principles from a design database. This work expands preliminary efforts [80, 81] to identify implicit principles for prototype design and fabrication through analysis of a DIY, open source sharing platform, Instructables.com. It has been observed that radical innovation is human centered, and includes novel interpretation of meaning [313]. This study has potential to combine these two elements.

5.2. Objectives and Approach

The study reported in this chapter consists of three elements. The first is an iterative extraction of principles from the online Instructables database. In the second phase, multiple parallel online raters help to test and refine the principles. The third phase is an experimental evaluation of the principles as part of design activities. Figure 5.1 provides an overview of this three-stage process. The goal of this research is to identify core practices embedded in the DIY movement. The objective of these efforts is to identify principles of prototype design and fabrication, and to explore their effects on design outcome. These objectives are stated as research questions in the following:

1. What fundamental principles exist for prototype design and fabrication, as embedded in Instructables' articles?
2. Do independent raters repeatably identify the same principles?
3. Is there a positive impact of applying the principles in design activities?

This project is scoped to explore Instructables in the Technology category of the web site as the prototypes in articles from this category closely map to prototypes of electro-mechanical products. The scale is similarly limited to hand-held and human-scale devices, as this is the focus of content in the Instructables database. This study is also restricted to principles of prototype design and fabrication. There may be other valuable process design insights in the database.

Research Approach

The three objectives of this two-year study, as outlined in the research questions, also map to the following sections. Section 3 provides a summary of the extraction process of the principles through iterative refinement and testing phases. This identification process is guided by foundational classification research [311, 314]. Section 4 provides results from multiple parallel online raters' validation and refinement of the principles. Section 5 reports observations from a controlled empirical study with comparative review of two groups of prototyping teams. Only one set of teams was exposed to the principles. The research methodology is graphically depicted from a high-level perspective in Figure 5.1.

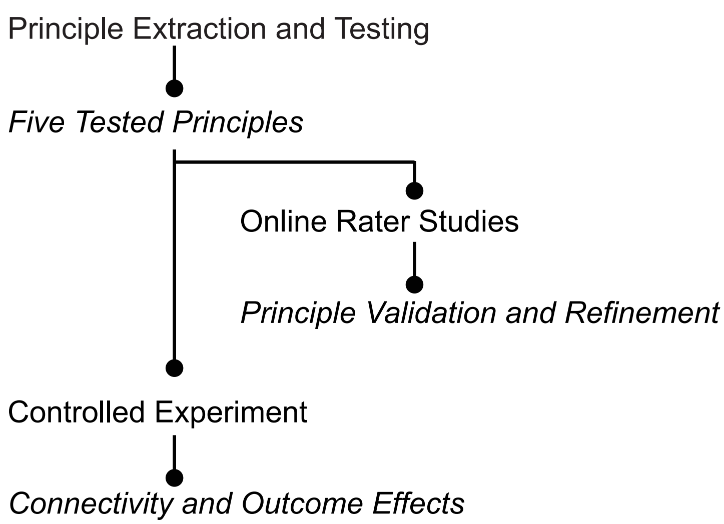


Figure 5.1: Overview of research methodology.

5.3. Principle Extraction and Testing

This section begins with an overview of the process by which principles were extracted from the Instructables repository. The following subsections report additional details regarding the construction of the repository itself, and details of the extraction procedure. The section concludes with definitions and examples for the principles.

A multi-stage procedure was employed to extract, refine, and validate principles from the Instructables repository. Literature review was employed to define a set of criteria for an actionable principle. The population size of the database was measured and an initial sample size for principle extraction was explored. Data saturation testing was employed on the results of this initial set. To refine the principles and remove potentially redundant concepts, a set of quantified tests was employed. Detailed information about each article was recorded to determine if a principle was present, as well as to more precisely define the principles. The quantified testing data was used as a starting point to bin separate potential principles which actually describe the same core phenomena. This binning process resulted in a set of five core principles. Finally, to achieve more significant results and to test the hypothesis that the principles are present across the population, a second and much larger set of articles was evaluated. These steps are graphically depicted at a high level in Figure 5.2. Note that several other validation procedures, other than the extended database testing, were performed as part of the overall study and are described in Sections 4 through 7.

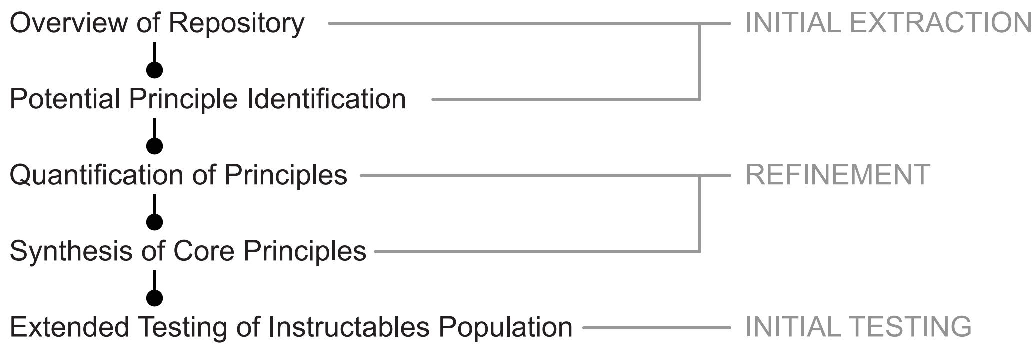


Figure 5.2: Overview of principle extraction and testing

Overview of Repository

Instructables.com was conceived at MIT Media Lab and developed by Squid Labs (Alameda, CA, USA). It is an online database for documentation and sharing of open source prototype designs. Articles on Instructables consist of a mixture of text, images, and often video instructions to guide construction of a design prototype. Although there is no formal requirement for the format of an article, the typical content consists of: required components, required tools, instructions for custom part fabrication and assembly, and documentation of the final design. Articles may also provide supplementary files such as .STL files for 3D components, PCB board design files, or programs for upload to a controller. The site reports meta-data on the articles. Meta-data includes the total number of views an article has received, as well as the total number of times a registered user has bookmarked the article for reference. Figure 5.3 overviews the categorization, and provides a screenshot from an article [315].

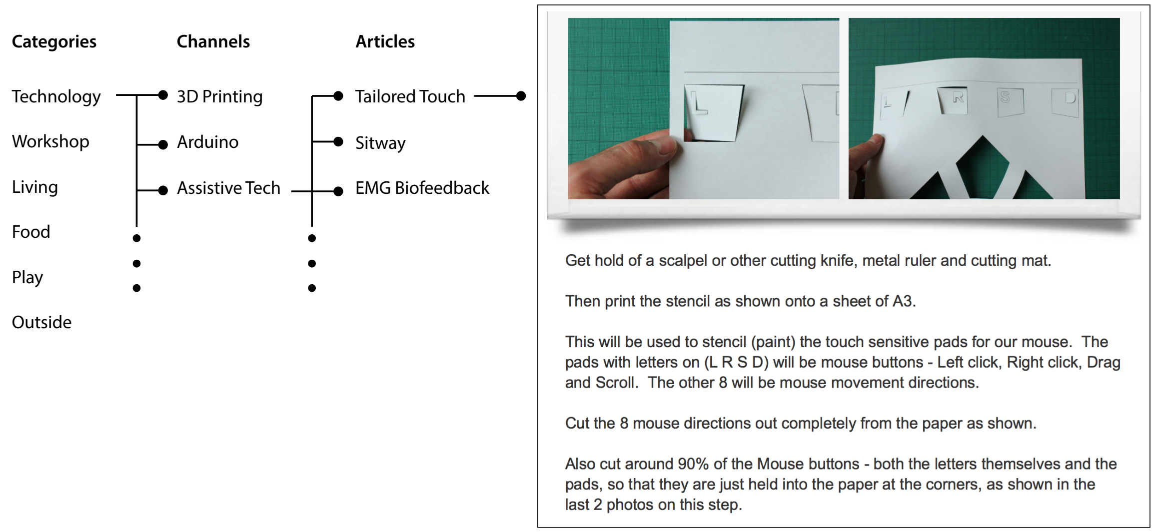


Figure 5.3: An overview of the Instructables repository. There are categories, channels, and individual articles. Note that only a sample is shown of the listings in each. The right hand side is a screen shot of a few steps within an article for prototyping a paper touchpad mouse. The article 'Tailored Touch' is an article in Assistive Tech, Technology [315]. Note the mixture of images and text for instruction.

As of January 9th, 2015 there was a total of 152,729 articles stored in the repository. Of the total, 37,370 were listed in the Technology category. Categories are independent groupings of articles. For example, another category is Workshop. Articles are not listed in more than one category. Articles in the Technology category map well to the scope of this study, which is the electro-mechanical product domain. The Technology category is further divided into 38 specific channels (e.g. Sensors, Biotech, Arduino). Articles from each of these channels were explored in the initial principle identification tests, details of which follow in the next section.

Potential Principle Identification

A set of criteria for defining a potential prototype design and fabrication principle were developed from review Koen's definition of engineering heuristics [21], as well as other seminal works on design principles [22, 80, 81, 307-309, 311-313]. These criteria are as follows:

1. Design oriented - the principle relates to an aspect of fabrication or design
2. Actionable - the principle describes a series of steps or actions
3. Objective paired - a specific benefit or objective is expected as a result of implementing the principle
4. Recurrent - the principle occurs in multiple articles

The first criterion is specific to the scope of this study, wherein only principles that relate to prototype design and fabrication are explored. Criteria two and three, are given requirements of design principles theory. A principle should be actionable and lead to a specific goal. The fourth criterion satisfies the requirement that a principle is not a specific solution, but a general guide that aids in developing a solution across varied contexts.

An initial set of articles was selected to explore the database for principles, and to determine the prevalence of principles within the population. To acquire this initial set, an equal number of articles (two) were selected from each of the Technology channels. This resulted in an initial sample size of 70 articles. Articles are only listed in a single channel, there is no cross listing. The content of articles between channels covers a large range of project type, from basic sensor design to articles for prototyping assistive technology. By taking articles from each channel, a higher degree of variety is expected. Articles were selected that described complete electro-mechanical prototypes. Articles which referred to other topics such as repair or supplied user-guide type instructions were not evaluated. Three channels did not contain any relevant articles, e.g. Linux. It is also important to note that the initial sample set of articles were the highest rated articles in the database with regards to meta-data (highest number of views, and bookmarks).

Although the meta-data may not be a direct measure of quality, it functions to filter incomplete or poorly constructed articles. For this initial test, the researchers closely examined these 70 articles, and listed detailed steps from each. Steps that described potential principles, i.e. met criteria one through three above, were highlighted and saved for continued analysis. Then potential principles that only occurred in a single article were removed to satisfy criterion four, above.

Data saturation was employed to determine if a sufficient sample set of articles had been evaluated to identify all of the potential principles. Figure 5.4 depicts the total number of unique principles found, after additional sequential analysis of each article in the sample set. It can clearly be seen that the number of unique potential principles reached a point of relative data saturation by the end of this initial study. Therefore, 70 articles was sufficient for initial testing.

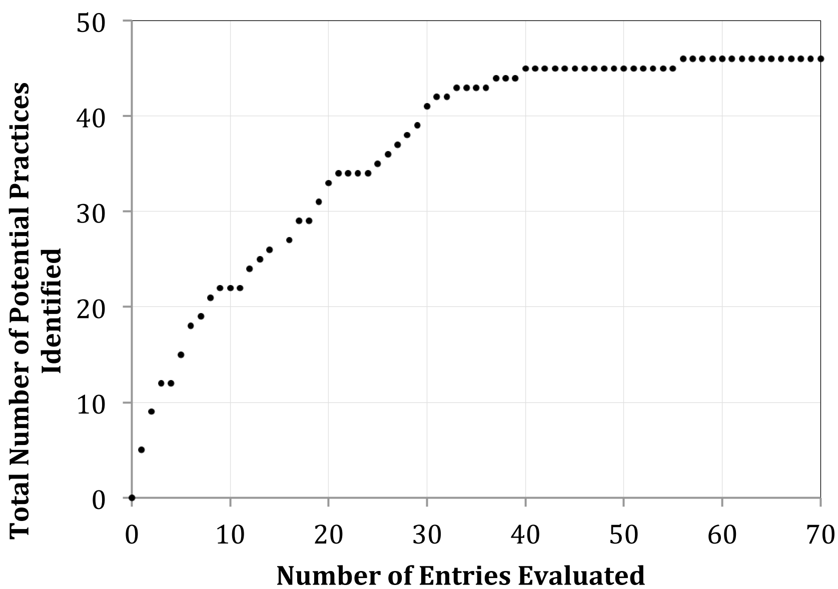


Figure 5.4: Data saturation for extraction of specific practices, or 'potential principles'.

Quantification of Principles

The set of potential principles were identified based on detailed process evaluation of the researchers. An additional series of tests was employed on the initial set of 70 articles to quantify the potential principles more precisely. This study consisted of identifying a concrete parameter that can be listed from each article in more detail to determine whether a principle was present or not. For each potential principle, a set of required test data was listed. These parameters are listed in Table 5.1

Feature	Recorded Parameter
All components	Source, cost, and function
Planning	Representation tools used
Custom components	Fabrication, and sequence
Structure	Reinforcement techniques

Table 5.1: List of data collected in the quantification study

From Table 5.1, features refer to a feature of the article and parameters of that feature which were recorded. Each component of each article was listed. Then the source, cost (when cited), and function of each of these components were also listed. This can be used to quantify the most common sources of components across the sample set. Planning refers to use of schematics, stencils, and CAD tools in the design. The use of these types of tools, as well as their stated objective were listed for each article. For custom fabricated components, the fabrication process used and fabrication sequence were also recorded (in addition to the source and cost of material and function of the component). The structure of the final design was also recorded. Components or features used to increase strength and durability were listed. This included listing joint types, use of fasteners, and placement of support members.

Synthesis of Core Principles

Information from the quantified testing was used to guide a synthesis, or binning, process. Potential principles which were found to functionally overlap were combined into a single core principle. Figure 5.5 represents a sample of several potential principles which were grouped under a single core principle. This process resulted in a final set of five principles. Inter-rater testing was employed to evaluate whether independent researchers would also identify the same principles. Independent raters were supplied with the criteria, a sample set of articles and asked to list potential principles. These independent raters found each of the five principles, after review of the articles. Although the additional raters used slightly different wording, agreement was reached that the core concept was the same.

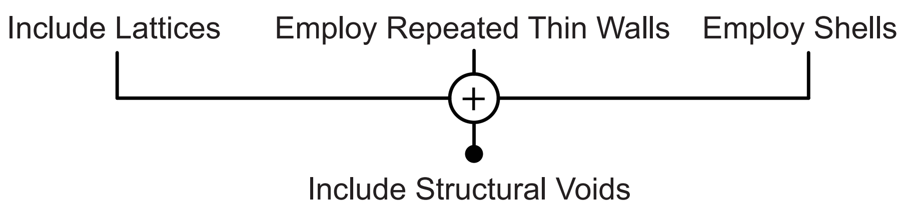


Figure 5.5: Sample of synthesis process. Three individual practices grouped into one generalized principle.

Extended Testing of Instructables Population

An additional set of articles was examined to determine if the principles occur outside of the initial sample set, and to add statistical significance to the testing. Sample size calculation was employed to determine the minimum sample size required to be confident that the sample set is representative of the instructables population. The goal was to achieve the 99% confidence level with a margin of error, or precision, of 0.05. For this calculation, Equation 5.1 was employed [316]:

$$n \geq \left(\frac{Z^2 P(1-P)}{d^2}\right) ; \tag{5.1}$$

where n is the minimum sample size, Z^2 is the statistic for a level of confidence (for 95% confidence, Z = 1.96; for 99% confidence Z = 2.58), P is the expected prevalence or proportion (which ranges from 0 to 1; for example if the prevalence is 20%, P = 0.2), d is the precision.

This equation requires an initial estimate of the prevalence of each principle in the repository (percentage of cases in which each principle is present). Therefore from the set of 70 articles, the prevalence of each principle in the sample set was calculated. Then this prevalence value was used in Equation 5.1 to determine a minimum sample size for each principle that would be required to achieve the target confidence levels. Since the prevalence varies by principle, so does the required sample size. The largest minimum sample size was 653 articles. However, to achieve a substantial safety factor, 1000 articles were reviewed. The first 30 articles (those with the most views and bookmarks) were taken from each Technology channel. Again, this approach is taken to ensure variety in the sample. To increase relevance to the electro-mechanical product domain, only articles with complete prototypes were included (this excludes articles focused on repair, or instruction manuals).

A reviewer closely examined each article in this expanded sample set to determine whether each principle was employed or not. As a result, a table of principle usage across the entire sample was constructed. This cataloguing procedure quantifies use of the principles with significant confidence levels. The results are summarized in Table 5.2. The goal of this analysis was to determine the relative prevalence of the principles across the database. Results were quality tested through inter-rater agreement. Pearson's correlation was $r = 0.68$ between raters for a sample set of 30 articles. This can be considered substantial agreement. The raters achieved full agreement after discussion.

Observations indicate that *hack commercial products*, and *employ basic crafting* are the most frequently present, and critical principles. Most articles employed several principles. The average was 3.84 principles per article (with $N = 1{,}000$), and the standard deviation is 1.2. These principles are introduced and defined in the following section.

Principle	**Articles that employ given principle**
Employ basic crafting	947
Hack commercial products	895
Prepare fabrication blueprints	734
Repeat fabrication processes	695
Include structural voids	105

Table 5.2: Results from extended sample study.

Introduction and definition of the principles follows immediately in the next subsection.

Definition of Principles

This section details the extracted principles. One approach for defining a principle is as a directive to achieve a given objective. In other words, a principle is a 'what' combined with a 'how'. This approach is used to present the five DIY prototype design and fabrication principles. A consistent linguistic and logic format is applied. Examples of each of the principles are provided in Table 5.3. Each of the principles can be applied to a varying degree. Examples of each are provided.

List of Extracted Principles:

- *Hack commercial products* to reduce the effort and cost required to achieve functionality (Table 5.3a). An existing product (or product subsystem) is repurposed, modified, and re-deployed as a subsystem in the prototype.

  Hacking is a means to reduce effort and cost required to achieve subsystem functionality. Hacking does not imply illegal modification of systems. Using commercial parts, as intended for a subsystem, does not constitute hacking.

- *Employ basic crafting* to reduce cost and effort required to acquire materials (Table 5.3b). Readily available materials are used to achieve complex function with reduced cost.

  Basic crafting implies use of tools and components that are readily available, easy to use and require little overhead maintenance or special training to operate; for the objective of reducing cost and effort. It is critical to have a deep understanding of relevant physical phenomena to avoid failure modes. Use of machinery, e.g. CNC milling, would typically not be considered basic crafting.

- *Prepare fabrication blueprints* to manage complexity and increase accuracy of fabrication (Table 5.3c). Sketches (sometimes even made onto components), stencils, CAD models, and schematics are used to directly aid in fabrication.

  This principle implies the use of any representation of the design for the purpose of managing fabrication complexity. An abstract design concept sketch would not be an example of this principle.

- *Repeat fabrication processes* to increase the efficiency of fabrication (Table 5.3d). Repetition is a means to reduce overall costs from fabrication. Multiple, functionally distinct components are made with a single fabrication process.

  The objective of this approach is to reduce startup costs. Preparing any machine or toolset for use has a certain associated cost. This principle strictly applies to custom component fabrication (not the purchase of COTS).

- *Include structural voids* to increase strength-to-weight ratio of the prototype (Table 5.3e). Elements such as lattices, hollow shells, or repeated thin walls are examples of structural voids.

  Aligning supports in a lattice can increase the strength-to-weight ratio of a prototype. Steel suspension bridges demonstrate structural voids, while traditional stone or concrete bridges typically do not.

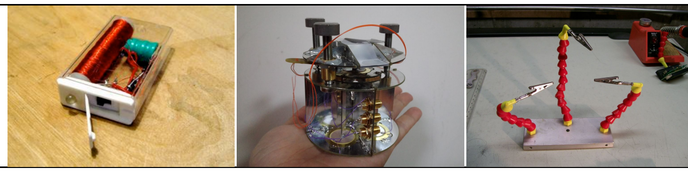
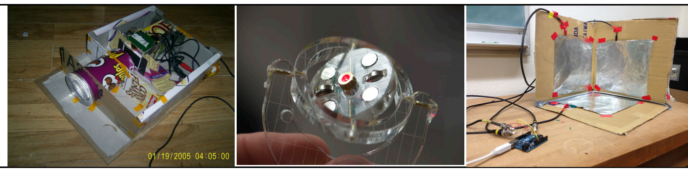
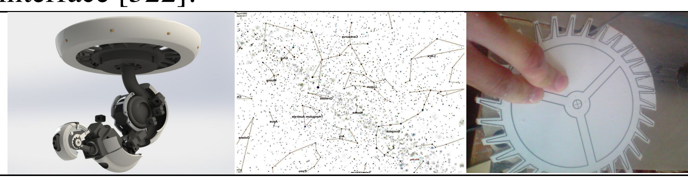
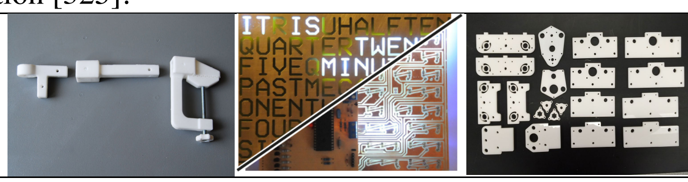
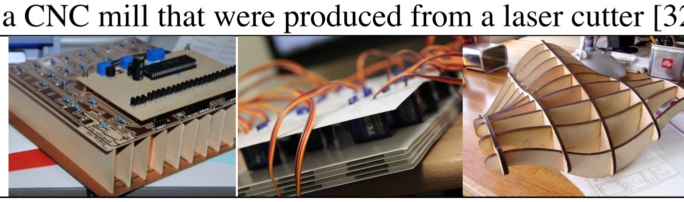

(a) *Examples of hacking commercial products*: (from left-to-right) candy bottle as casing for inductively chargeable flashlight [317]; DVD read head as probe controller for atomic force microscope [318]; flexible tubing as supports for third hand tool [319].

(b) *Examples of employing basic crafting*: (from left-to-right) cardboard as structure for projector [320]; acrylic sheet, permanent magnet, and laser pointer for 3D magnetic field mapping tool [321]; aluminum foil, cardboard, and Arduino for 3D motion capture interface [322].

(c) *Examples of preparing fabrication blueprints*: (from left-to-right) CAD model of robotic lamp [323]; schematic star map for fiber-optic star portrait [324]; paper stencil for gear fabrication [325].

(d) *Examples of repeating fabrication processes*: (from left-to-right) 3D printed components of a clamp for a modular quad-copter design [326]; custom printed circuit board, and light stencil both fabricated with an inkjet etching process [327]; several components for a CNC mill that were produced from a laser cutter [328].

(e) *Examples of including structural voids*: (from left-to-right) a display with repeated thin walls for support [327]; A paper mechatronic system with paper repeated thin walls [329]; a laptop stand with structural lattices [330].

Table 5.3: Example instructables that exhibit the fabrication principles.

5.4 ONLINE RATER STUDIES

This section will report results of a study using an online survey tool. The objective of this study is to test whether a set of reviewers, who have not been exposed to the research hypotheses, will identify the same principles as the researchers found during analysis of the sample set of articles. As seen in Figure 5.1, the online study provides potential for validation and refinement of the principles. The section begins with an overview of the benefits and limitations of crowdsourced analysis, then follows with a brief discussion of pilot studies. The section concludes with design of the complete online study and results.

Introduction to Crowdsourcing

Online crowdsourced analysis combines parallelization of computational analysis with the advantages of human reasoning [331]. Parallel decomposition of problem solving is inspired by the search for extra-terrestrial life at home or 'SETI@home' project. In this effort, millions of individuals shared the computational power of their home PCs for an astronomy data mining task [332, 333].

Parallel decomposition has also been demonstrated with tasks requiring human intelligence. One example is the Foldit project. In this project, individuals solved complex protein folding problems via a game-like environment. A result of this project was successful identification of the precursor pathway for a critical enzyme that could potentially lead to renewable fuel production [334]. Online raters have volunteered to provide distributed ecological monitoring [335], identification of astronomical bodies, and quantum physics modeling [336].

Crowdsourced analysis provides refinement and validation of the DIY prototype design and fabrication principles. This approach helps in refinement and error checking [337]. This method has potential risks, as anonymity of the workers may influence participation styles [338]. Workers are the anonymous participants who complete the online surveys. A subset of workers provide blank responses or copy text using automated submission algorithms or 'bots' [339]. It is critical to employ a design task and reimbursement structure that encourages quality responses [339, 340]. Design of the survey can also affect outcome. General observations of this research and previous studies are that less abstract tasks achieve higher result quality [341, 342]. For this study, Amazon's Mechanical Turk platform was employed. This platform was chosen because of its relatively large user base and flexible design interface.

Pilot Studies

A series of pilot studies was conducted to inform design of the surveys. Previous research provided some insights on basic details such as reward levels [340]. Pilot surveys were also conducted in which various question formats were evaluated. One observation of online survey design is the important consideration that the audience will have no context for the survey. In many studies, the researchers may approach a design firm, or work with students in a design class, wherein these is some implicit expectation that the survey will relate to design. With online studies there is no such context and the survey itself must fully orient respondents with the nature of the work. However, with several iterations a survey design was achieved for which 91% of responses were relevant to the study. A relevant response is both not blank, and directly addresses the topic of the question.

Data saturation testing was also employed to determine how many parallel raters should answer each survey. A sample set of surveys was posted to the online tool. Parallel raters were permitted to respond to the same survey. Then the researchers counted the number of unique solutions provided by each additional rater for each survey.

This was used to compose a data saturation test. A logarithmic curve was fitted to the data. If more than 25 raters evaluate the surveys, the expected marginal gain of new unique solutions per new rater is less than 1% of the total number of unique solutions found by the first 25 raters. Therefore, 25 raters is taken as sufficient for data saturation. The r^2 value for the equation fit was 0.99.

Full Online Study and Results

There were two sets of surveys deployed in the full study. The first set of surveys acheives high depth of analysis from a set of raters. The second survey set receives a higher level asssessement from a larger set of raters. This format helps ensure that there is both detailed analysis and statistical significance to the study.

In the first stage, five articles were selected for each of the five principles. Twenty-five raters assessed each article. For these articles, control was introduced by posting all five of the principle variant surveys for each example. Some of the examples exhibit up to three principles but the researchers did not identify all five principles in any of the posted samples. Therefore there is an opportunity to match both positive and negative identifications between the respondents and the researcher. This initial set of twenty-five examples was evaluated using a survey where respondents provide an open-ended response to determine presence of a principle. A corresponding binary 'yes/no' indication of principle presents is provided afterwards. This provides an initial test for matching with detailed answers from the respondents. There was a high degree of matching between the open-ended reply and binary testing for the principle.

The second, large sample size, survey set was deployed with a binary principle test. For this set, there were 125 example articles that had each been rated by the researcher to contain one of the principles. There were 25 examples for each principle. A total of 4,385 online assessments was made accross both of these stages.

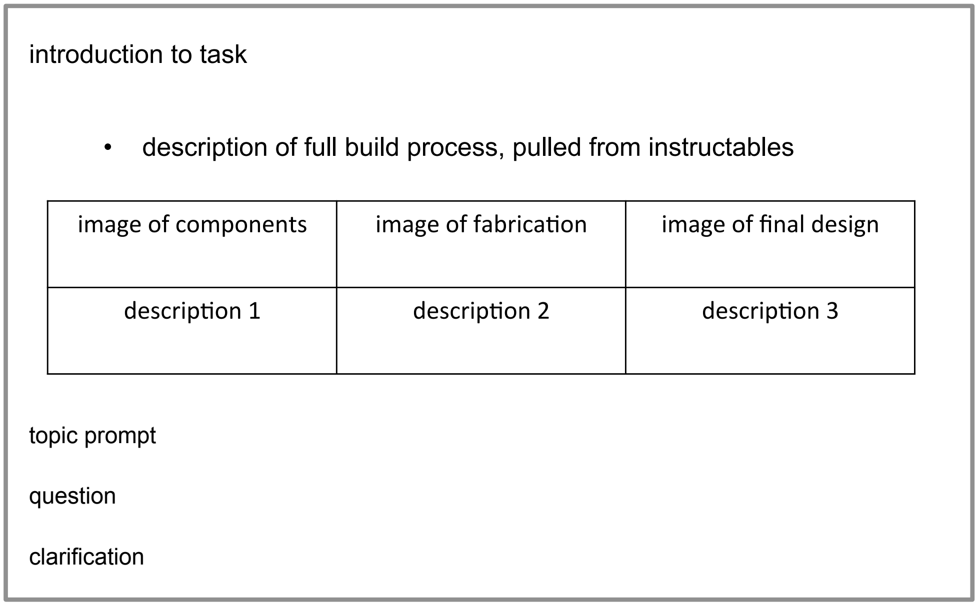


Figure 5.6: Schematic layout of the survey design. Each survey was populated with images and description from a specific article. The questions at the end of the survey varied, and are described in Table 5.4.

Topic prompt	Question	Clarification
Design	What do you notice to be most clever about the design or construction of this prototype?	Describe it generally- so that someone else might be able to do the same thing for a similar design.
Part Selection	What was clever about the selection or fabrication of parts for this prototype?	Describe it generally- so that someone else might be able to do the same thing for a similar design.
Fabrication	What was most clever about the construction process used for this prototype?	Describe it generally- so that someone else might be able to do the same thing for a similar design.
Schematics	What was clever about the choice of schematic, or to not use a schematic, in this process?	Describe it generally- so that someone else might be able to do the same thing for a similar design.
Structure	What is the most clever structural (strength adding) feature in this prototype?	Describe it generally- so that someone else might be able to do the same thing for a similar design.

Table 5.4: Question Variants for the full online survey. Each article was posted five times, once with each set of questions.

The technique of multiple raters is adapted from Green [343]. Fleiss' Kappa is a metric for determining the level of agreement between many parallel raters. It is analogous to Pearson's correlation. Fleiss' Kappa was employed to evaluate the agreement between parallel online raters. Due to design of the crowdsourced platform used, each of the raters did not necessarily complete more than one article. For this case, since the minimum number of assignments given by a rater is only one ($n = 1$), the form for Fleiss' Kappa is simplified as in Equation 5.2 (below).

$$P_i = \frac{1}{n(n-1)}\left[\left(\sum_{j=1}^{k} n_{ij}^2\right) - (n)\right] = \kappa \; ; \qquad (5.2)$$

where P_i is the agreement for raters on a given topic (principle), n is the number of subjects (articles) evaluated by each rater, the categories are indexed by j from 1,..,k; and n_{ij} represents the number of raters who assigned the i^{th} subject to the j^{th} category; Note that $P_i = \kappa$ only in this special case where N = 1.

The Fleiss' Kappa is used to develop a ‘Synthesized Rater’. In effect, only those results with high agreement can be considered as significant. These significant positive identifications are compared against the researcher's initial observations for identifying the principles. In this study, a positive identification of a principle in an example is considered only in cases where Fleiss’ Kappa agreement is above $k = 0.8$ between raters that the principle was present.

Agreement results are shown in Table 5.5. Table 5.5 provides a summary of agreement and disagreement between the researcher and the Synthesized Rater. For each principle, 30 articles in which the researcher found the principle were also assessed by the online raters (as detailed above). Table 5.5 reports the number of matched ratings for each of the principles. For example, for the principles *Hack commercial products*, both the researcher and the Synthesized Rater agree that a principle was present in 29 cases. There were also 18 negative cases (without principle) explored. These are not included in the table for the purpose of clarity. Pearson’s correlation between the researcher and the Synthesized Rater is $r = 0.85$ for across the full set of samples. Overall, this study provides confirmation that the researcher and outside raters agree on presence of the principles.

Principle	Synthesized Rater found	Synthesized Rater did not find
Hack commercial products	29	1
Employ basic crafting	29	1
Prepare fabrication blueprints	28	2
Repeat fabrication processes	29	1
Include structural voids	29	1

Table 5.5: Principle identification matches between researcher and Synthesized Rater. Thirty articles were tested for each principle.

5.5 EXPERIMENTAL EVALUATION

A controlled experiment was employed to evaluate use of the principles in design. Participants were undergraduate students in engineering product development at the Singapore University of Technology and Design (SUTD) in their second year. Participant demographics were not controlled or selected for; the only requirement was participation in the design project. Participants took one week to intensively design and construct a prototype. The groups completed their design projects independently. For the control group, a traditional stage-gate prototyping methodology was adopted [1, 287].

In the experimental group, the principles were introduced via presentation and examples. Participants in the experimental group also provided self-evaluation via survey. There was a total of 550 individual participants in the study. Participants were those students who opted to provide data for the study. The design tasks were completed by teams of five individuals. The control group had 61 teams, and the experimental group had 49 teams. This difference is due to the volunteer nature of providing data. The control and experimental groups focused on design of a cooling system for automated milk delivery and design of systems that demonstrate a phenomenon in mechanics. These projects were both part of the 'designette' curriculum [53, 54, 344]. Scope, requirement stringency, and variety among solutions were equivalent from the projects. Project budget, time allocation, and prototyping requirements were also the same. Participants all had equal opportunity to prototype. Figure 5.7 shows an example solution from an experimental group. The principle *Repeat fabrication processes* applies to the wheels, structural supports, and inertial energy storage flywheels, which were all laser cut. The principle *Include structural voids* applies to the chassis.

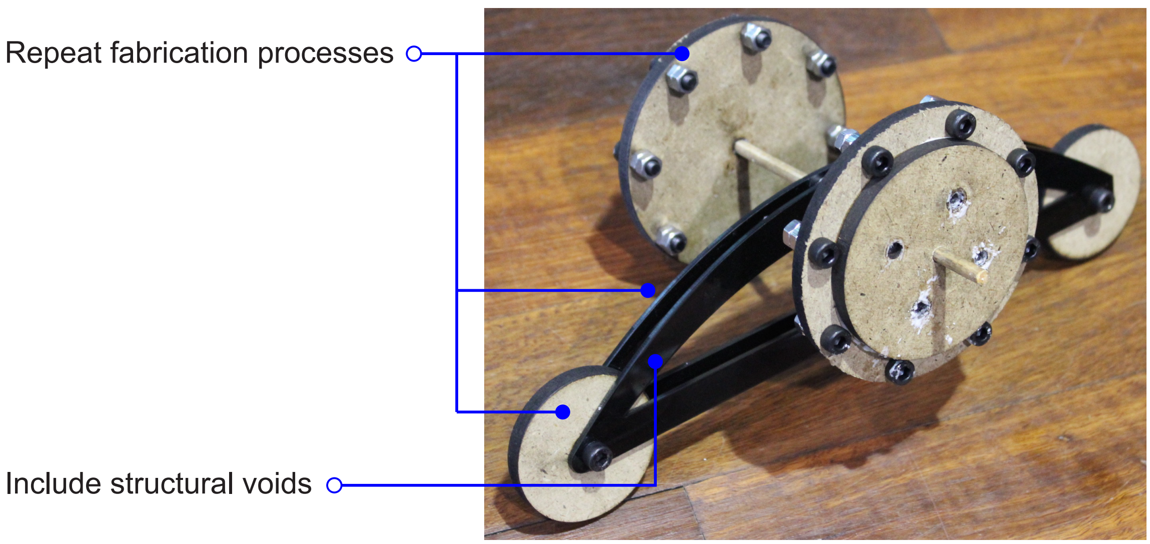


Figure 5.7: Sample prototype from experimental group.

Experimental Results and Findings

The experimental group implemented significantly more principles in their prototypes. This finding was determined by two independent raters who listed the total number of principles implemented in each physical prototype. Prototypes were analyzed by reviewing photographs of the prototypes and through review of each team's final reports. Pearson's correlation between the raters was $r = 0.85$. This analysis provides an evaluation of the connectivity of principles. This difference is significant with Students *t*-test at $p < 0.01$ (shown in Table 5.6). The control groups did on average apply two or three of the five principles in their prototypes. This result indicates that the principles can be utilized, at least in part, through intuition or experience. However exposure to the method can increase the degree of implementation. Teams in the experimental group implemented roughly the same number of principles in each prototype as were found in Instructables on average for the extended study. There was no significant difference between the experimental group prototypes and Instructables in number of principles.

Group	Average number of principles	Standard Error
Experimental group	4.0	0.13
Control group	2.9	0.14
Instructables articles	3.9	0.04

Table 5.6: Implementation of principles across groups.

Prototypes in the experimental group were also rated by a panel of external judges at the end of the project (the control group finished their prototypes in an earlier term). Of all teams in the experimental group, eleven were chosen to enter a final competition round as part of the design project. This decision was based on design and execution. It was observed that the teams in the final competition employed more principles in their prototyping, on average, than other teams. These results are summarized in Table 5.7. The difference is significant with Student's *t*-test at $p = 0.05$.

Group	Average number of principles	Standard Error
Teams in Final Competition (n = 13)	4.4	0.14
Other Teams (n = 37)	3.9	0.16

Table 5.7: Principle use between teams in the final competition and other teams.

A third metric used to evaluate design outcome was the number of teams that completed physical prototyping. A certain percentage of teams only provided a design concept rather than a working prototype. This is a performance measure for overall success of the process. A direct comparison is made between the normalized percentage of teams that completed a prototype between the experimental and control groups. In the control group, 51% of teams provided evidence of prototyping (documentation of a physical build). In the experimental group, 91% of teams provided evidence of prototyping. Using a transformed *z*-test for difference of proportions of two defective proportions the p value is < 0.001. This is sufficient to reject the null hypothesis that the difference in prototype fabrication occurred by chance.

Evaluation of Surveys

Self-assessment survey results indicate specific effects of implementing the principles. Survey questions were designed to evaluate the impact of each individual principle. This survey was completed by participants of the experimental group. Results are grouped by those teams that reported use of a principle or not. Participants gave a Likert reply from the range: (-2) strong disagreement, (-1) disagreement, (0) neutral, (1) agreement, and (2) strong agreement. These replies correspond to each of the column-questions (individual metrics) in Table 5.8. Use of the principle was reported as yes/no only by participants. There were a significant number of reports that applying the principles leads to increased durability and accuracy of prototyping. Several of the results were inconclusive, which may be due to sample size or the inherent limits of self-assessment.

Principle Condition	**Question A**	**Question B**
Hack commercial products	**Components were easy to find**	**Component quality was high**
used hacking principle	0.1	0.6
did not use	0.1	0.4
Student's t-test, p =	0.482	0.313
Employ basic crafting	**Fabrication required minimal effort**	**Fabrication quality was high**
used basic crafting principle	0.8	0.5
did not use	0.6	0.7
Student's t-test, p =	0.356	0.304
Prepare fabrication blueprints	**Schematics were accurate**	**Schematics were helpful**
used blueprint principle	**1.2**	**1.4**
did not use	**0.7**	**0.7**
Student's t-test, p =	**0.010**	**0.003**
Repeat fabrication processes	**Fabrication required minimal effort**	**Fabrication quality was high**
used repetition principle	0.5	0.7
did not use	0.2	0.4
Student's t-test, p =	0.239	0.126
Include structural voids	**The prototype was durable**	**The prototype was light**
used structure principle	**0.9**	0.6
did not use	**0.3**	0.3
Student's t-test, p =	**0.013**	0.186

Table 5.8: Results of surveys, significant results in bold font.

5.6 Applied Case Studies

Two case studies are reviewed in this section in which the researchers employed the DIY fabrication principles. The first prototype was designed to serve as an example in a fluid mechanics course at SUTD (Figure 5.8). The course project was to develop a cavity flow system. The prototype was of a lid-driven type cavity flow system. Three principles were applied in the development of this prototype. The *Prepare fabrication blueprints* principle was employed to design the interfaces and system structure before fabrication began. The *Hack commercial products* principle was employed for the casing. It requires significant time and iteration to build aesthetically clean water-proof chambers. By recycling a fish tank as the casing, the effort to develop a highly visible waterproof chamber was vastly reduced. The *Repeat fabrication processes* principle was used in several components. The drive shaft, passive rollers, and structural supports were produced with a fused deposition modeling machine. The timing belt and inner casing components were laser cut. This approach significantly reduced the number of components that needed to be purchased or fabricated with other processes.

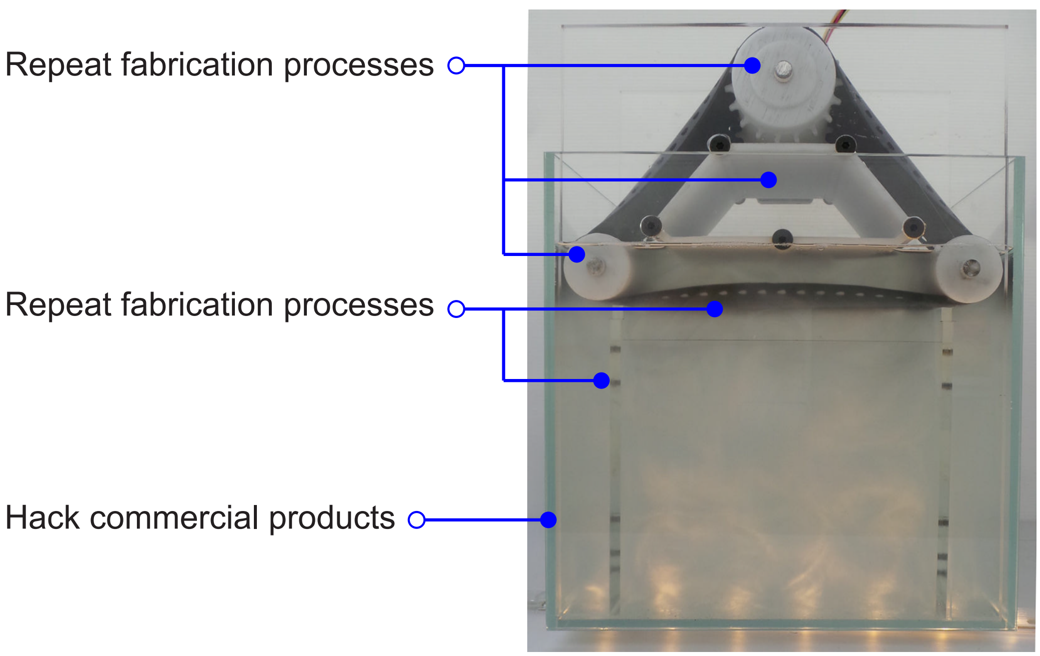


Figure 5.8: Case study, development of a lid driven cavity flow chamber.

The second case study is a hand-held optical mouse (Figure 5.9). This example was adapted from an Instructable. It is designed to be a mouse for presentation and large-screen Internet browsing. Several principles were applied. The *Hack commercial products* principle was essential as the track ball is actually harvested from a personal care product and attached to the mouse. Additionally, the mouse is not custom designed, but rather repurposed. The *Employ basic crafting* principle was critical to simplifying the process. The only custom fabrication involved was using scissors to adjust the shape of the track ball base, and adhesive to attach the trackball to the mouse. This level of simplicity is directly inspired by the principles. It is a general observation that the principles can vastly reduce the effort of prototyping. Potential limitations were also observed and are included in the discussion section.

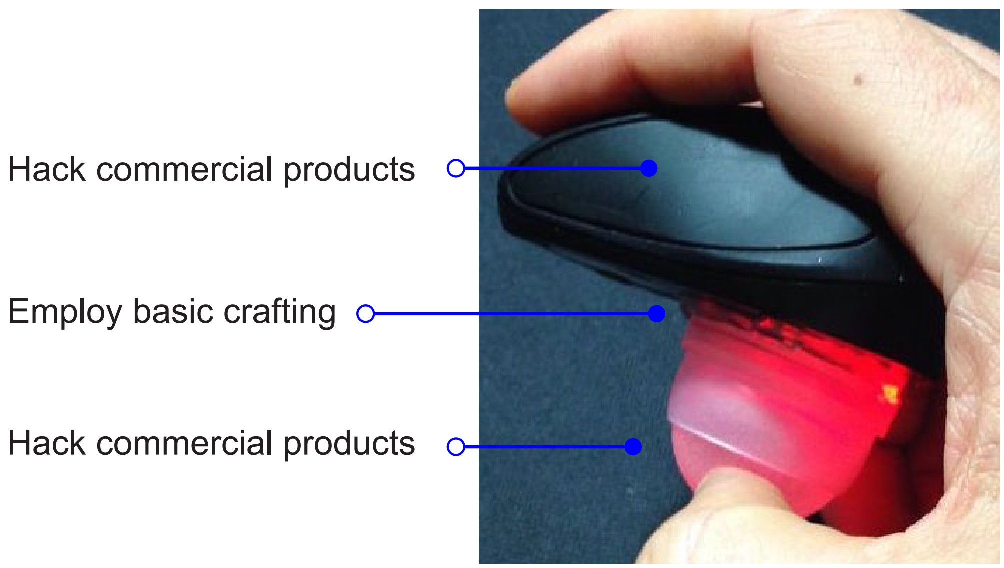


Figure 5.9: Case study; development of a handheld optical trackball mouse.

5.7 Discussion

Five unique DIY prototype design and fabrication principles were identified. These were extracted through iterative analysis of the open source database Instructables.

The assessment of multiple parallel online raters provided substantial validation and refinement of the principles. The outcome of introducing the principles in a design context was also tested. There was generally a high of adoption of the principles by participants in the experimental group (high connectivity). Teams in the experimental group successfully prototyped more often than the control. Teams that were selected for final competition in the experimental group also employed more principles, on average, than teams that did not. Each of the principles has unique benefits and possible limitations.

The *Hack commercial products* principle can result in reduced effort of development. It may at times be challenging to identify sources of components to hack. This in and of itself is also a skill that requires some experience. The *Employ basic crafting* principle is effective to reduce the cost and effort of fabrication. It may be difficult to produce prototypes that are durable over long cycle lives using this method. The *Prepare fabrication blueprints* principle can aid in the management of complexity. It may enable the production of complex shapes without digital manufacture. It may potentially incur additional design time to develop schematics, stencils or blueprints, and there is a subsequent tradeoff between time spent and quality increase. The *Repeat fabrication processes* principle may reduce the cost of fabrication. It can also save wasted material to use one process, and potentially make custom fabrication more viable for prototyping. However, there are times that is simply not feasible to produce all parts with one process. The *Include structural voids* principle is critical to develop light and durable structures. Including lattice structures or repeated thin walls can improve the strength-to-weight ratio of the prototype as a whole. This approach may increase fabrication time or complexity.

Limitations and Future Work

One limitation of the study is a potential variable in the prototypes due to the fact that the experimental and control groups addressed slightly varied design problems. This aspect may have implications in the results via indirect influence. This limitation is mitigated by the relatively similar design context of the two course projects. Although they are slightly different, they are both designette activities, conducted with similar sample sizes, participant skill levels, available materials, processes, and final requirements for providing a design concept and final report.

The research approach taken was to test for repeated principle use in the database. This approach, however, does not allow for identification of approaches that have potential to positively impact design, but were only present in a very small number of cases. One benefit of this approach is that it substantially reduces the risk of a 'false positive' or identifying a principle that is not generalizable. However, future research could potentially explore evaluating the potential for non-repeated principles. One possibility to achieve this goal would be to extend the crowdsourcing analysis to include sorting and selection of articles as well as analysis of articles.

Open avenues include examination of other databases, identifying marginal effects on cost and time expense associated with each principle, and exploring means of representing the principles for use in design contexts.

Chapter 6: Conclusion

CONCLUDING REMARKS

The design prototyping methods explored in this work are intended for integration with a comprehensive design approach. Such a method involves careful consideration of the design problem, and establishment of the true stakeholder requirements. Other factors such as manufacturing, or logistical concerns of product deployment are also critical to a comprehensive method. There are seminal works on the broader topic of engineering product design [1, 287]. The intention of this work is to expand and explore techniques within the critical subtopic of design prototyping.

The traditional engineering design approach strongly emphasizes the importance of testing. However, there are not currently any widely accepted methods to systematically guide prototyping efforts. This work functions to enable systematic testing of design concepts with a well-planned prototyping effort. In particular, the traditional stage gate approach, which progresses in a sequential fashion from low-fidelity models to functional prototypes, is re-visited and expanded into a larger dimensional space; as described in the strategy method. This approach directly encourages deeper consideration of the objectives of a prototyping effort. It also guides the designer through identification of techniques which may reduce cost, or improve performance of the final outcome. In a complementary fashion, the DIY principles provide a unique set of tools to inform the development (embodiment) of prototypes.

Often, in challenging design contexts, the development of a prototype can seem daunting or logistically infeasible. However, the DIY principles (in concert with the strategy method) provide an avenue for producing functional prototypes with increased efficiency. The methods function to codify the leap between the logical objectives of the design effort, with an individual's intuitive design and fabrication experience. This codification also addresses the critical need of enabling prototyping in cases where a project has apparently high risk or uncertainty and the design team may be averse to early testing. Although there is an apparent increase in time expenditure when exploring strategy methods or parallel concepts, there is often a potential for improved performance. It is also essential to support these efforts with techniques such as requirement relaxation, subsystem isolation, or scaling to reduce time and resource expenditure. Low risk prototyping is ultimately an enabler of innovation.

The methods may also enable designers to explore techniques with which they are not familiar, or to re-evaluate potentials strategies for a given context. The techniques are presented both individually, and in one integrated version (the strategy method). An individual or design team can use the presented information as the foundation to develop a novel or customized strategy and/or hybrid methods in their own context. The design team might also potentially revisit the index tool, strategy tool, or DIY principles throughout the prototyping process and employ them at multiple stages. The development of physical models is enabled through implementation of prototyping techniques, and methods.

This work was constructed to closely map evaluation of individual research objectives to individual contributions. The individual contributions support the overall research objective to identify, evaluate, and expand upon methodological tools and techniques for design prototyping. They are as follows:

- Review and evaluation of existing methodological tools and individual techniques for design prototyping and summary for key empirical research insights with indexed overviews of subtopics.

- Deployment and evaluation of a novel geometric path length technique for modeling a particular design case. This method is a hybrid technique consisting of relaxation of requirements and virtual prototyping.
- A series of empirical studies was conducted to evaluate the marginal effects of iteration and five other individual prototyping techniques. Alongside this evaluation, a strategic method based on heuristics for best practices from the literature was also developed. The outcome effects of introducing this method to experimental teams were also determined.
- The Instructables repository was extensively reviewed to determine five novel design and fabrication principles for prototyping. Open sourced crowdtesting was used to validate the presence of these principles. The design outcome effects of employing these principles by design teams was also compared to a control set of teams deploying a stage gate prototyping method.

These individual findings provide a groundwork for evaluating several important aspects of prototyping. The objectives and best practices of prototyping are provided at high level. This summary of foundational information provides insights for continued research in prototyping, as well as the practice of design prototyping. The strategy method provides guidance for implementing these practices in design contexts and also functions as a datum for comparison with future methods. The DIY principles provide a novel means to achieve lower cost, rapid prototyping, with high functionality.

This work as a whole provides a substantial contribution to research in the field of design prototyping. Previously there were no tools to cross-evaluate the existing techniques and empirical findings, to plan a strategic effort for a specific design problem, or to increase efficiency and functionality of prototype fabrication.

LIMITATIONS

The research reported in this dissertation is limited in several aspects. The first is a limitation of scope. The studies are all restricted to the development of electro-mechanical products. The controlled studies are also limited to products on the human scale. However, the empirical research and case studies include investigation of large scale products (e.g. ships), software interface design, and architectural design cases. The controlled studies do include variance in problem type and duration. This limitation of scope is intentional, as this work is primarily intended for use by electro-mechanical product developers. There may be parallel research opportunities in other product domains.

The second overall limitation is in experimental design. Most of the tests for significance in this research involve use of the $p = 0.05$ value as sufficient to reject the null hypotheses for various testing procedures. However, the expected robustness of this value is that only nineteen out of twenty cases of null hypothesis rejection are accurate, from the fundamental statistical view point. To mitigate this limitation, multiple studies are conducted in parallel. Each individual study has several detailed limitations which were reviewed in the respective chapters.

DIRECTIONS FOR FUTURE RESEARCH

This research has provided an empirical foundation for a number of future directions. These directions include both enhancement and refinement of existing knowledge as well as potential identification of fundamental new areas of research. Several specific insights for future research which emerged as part of the studies in this dissertation are as follows:

Individual techniques

- What are the marginal effects of individual techniques other than iteration, such as a parallel prototypes, scaling, etc.?
- What are differences in the problem solving style between virtual and physical prototyping, and other individual techniques, as determined by detailed time tracking protocol studies?
- Given the variance in each individual's fabrication skill, could an instrument (such as a basic fabrication task) be developed to add assessment an individual's prototyping experience level within protocol studies?
- What are the effects of implementing each individual technique in early design stages versus later stages?
- What are the capabilities and limitations of various hybrid individual techniques?
- Can a full regression model with interaction effects be determined for individual techniques, with respect to design outcome?

Strategic methods

- What additional insights could be gained regarding the strategy method through conduction of time-dependent protocol studies?
- Can a more complete strategy method be developed that includes additional individual techniques, material selection, or fabrication method?
- How might the strategy method be altered to adapt to a design problem as it changes over time?
- How can strategic methods be integrated with other design tasks?
- Are other representations of the strategic method more effective (e.g. exemplar cards, design tracking notebook)?

DIY inspired design

- How can design research evolve with concepts emerging in the DIY design community?
- What are marginal effects and interaction effects of the DIY principles identified in this dissertation?
- Are there other design repositories that would offer unique design insights (e.g. Shapeways, Kickstarter)?
- How can principles be identified which occur only in single design cases?
- Can more detailed methods (e.g., strategic methods) guide execution of the DIY principles in more detail?

Other prototyping topics

- What other possible directions can be explored with parallel human intelligence task decomposition (crowdsourcing and crowdcrafting)?
- Can advanced ideation methods (e.g., C-Sketch) be mapped to prototyping?
- How can more detailed insights be gained from protocol and even neurological observation studies of prototyping activities?
- What design tools would aid in capturing and developing full capabilities of additive manufacturing?
- What additional insights emerge when the methods are applied to larger scale and longer term case studies?

There are many possibilities for developing tools and methods relating to prototyping. The above list is not meant to be exhaustive, but rather to open consideration of potential areas which may offer insightful results in the near future.

Appendix

Technique	Context Variable	Heuristic	Assessment -2 Disagree Strongly	-1 Disagree	0 Neutral	1 Agree	2 Agree Strongly
Iteration	(performance)	There is potential for significant performance increase					
	(fabrication)	A fabrication method can be chosen that will permit iteration.					
	(resources)	The expected cost of iteration is relatively small compared to the total budget.					
	(time)	The expected time to iterate is relatively small to the total project timeline					
	average the above	Low average: pursue one only. <--> High average: pursue several iterations.					
Parallel Concepts	(resources)	There are sufficient resources to prototype multiple concepts.					
	(time)	There is sufficient time to prototype multiple concepts.					
	(ranking)	Rankings of several concepts are very close (e.g. from Pugh chart).					
	average the above	Low average: pursue one only. <--> High average: develop multiple concepts.					
Scaling	(models)	Scaling law(s) will permit accurate system modeling via a scaled build.					
	(feasibility)	Scaling will significantly increase the feasibility of prototyping.					
	average the above	Low average: use a full size model. <--> High average: use a scaled model.					
Subsystem Isolation	(interfaces)	Interfaces between subsystems are predictable and re-integrable.					
	(requirements)	1 or 2 subsystems embody the critical design requirements.					
	(resources)	Testing a subsystem would substantially reduce expense of resources					
	(testing)	Testing of an isolated subsystem will validate a key function					
	average the above	Low average: integrate the system. <--> High average: isolate subsystems.					
Requirement Relaxation	(requirements)	The requirements require refinement					
	(concept)	At this stage, concept development is the most critical					
	(resources)	A reduced requirement prototype will significantly reduce resource usage.					
	(usage)	At this stage it is important to simulate usage scenarios					
	average the above	Low average: use rigid requirements. <--> High average: relax requirements.					
Virtual Prototypes	(effort)	Virtual prototype(s) will reduce effort compared to a physical one(s).					
	(availability)	The required tools to develop a virtual model are available					
	(data)	A vritual model will provide accurate test data					
	(design)	A virtual model will facilitate other needs: complex topology, integrated testing					
	average the above	Low average: use a physical model. <--> High average: use a virtual prototype.					

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