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DESIGN PROTOTYPING OF SYSTEMS

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Abstract

In recent years, groundbreaking work in design science has identified that prototyping is one of the most critical factors leading to successful development. Many decisions regarding the detail of a design and the allocation of resources are made during design prototyping. Extant studies provide foundational insights in strategic prototyping. This work explores prototypes for developing services and systems that are complex. A framework is proposed to visualise strategic prototyping to search design spaces that span multiple domains. We define three phases of system prototyping: partitioning, search, and implementation. The framework illustrates the relationship between individual techniques and associated cost versus performance outcome. This new framework is supported through two commercial development case studies that demonstrate the approach. The first is a subsystem from a hybrid launch vehicle development effort at Gilmour Space Technologies, the second is a service centre design case from the SUTD-MIT International Design Centre.

Keywords: Design costing, Complexity, Design methods, Systems Engineering (SE), Product-Service Systems (PSS)

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1 INTRODUCTION

Prototyping is one of the most critical factors in successful design (Otto and Wood 2001). Many decisions regarding the detail of a design and the allocation of resources are made during the prototyping phase of design (Gero 1990). Previous research has identified strategies for planning individual prototypes (Bradley Camburn *et al.* 2015, Bradley A. Camburn *et al.* 2015). However complex products, services, or systems often require multiple streams of prototyping efforts to be co-ordinated. This paper provides a graphical framework for visualizing complex search strategies. In this work, we define three phases of systems prototyping: partitioning, search, and implementation. The framework illustrates a relationship between techniques used in each these phases with associated cost and performance outcome. This approach to model systems prototyping efforts is then demonstrated through two case studies in systems design. One is for an integrated medical service facility. The second is for one subsystem of a commercial hybrid launch vehicle from Gilmour Space Technologies. This work explores the following research questions:

1. What are the relationships between prototyping techniques, cost, and performance?
2. Can traditional (and more complex) prototyping strategies be viewed in a graphical way?
3. Is the given mapping approach applicable to both service and system prototyping efforts?

A model of the way that designers prototype is presented. This is supported by quantitative cost and performance based models for individual prototyping techniques, and validated through systems design case studies. The modeling approach is provided to visualize the embodiment of systems prototyping and the relationship between multiple prototypes in a design effort. This tool, alongside the empirically validated cost and performance models provides a platform for comparing various possible 'search strategies' to explore the space of possible designs.

2 PARTITIONING

For the design of systems, it is often necessary to segment the design problem in some way (Reed Doke 1990, Drezner and Huang 2009). With what are referred to as 'wicked problems' solutions are typically multi-faceted or complex and it is infeasible to develop the entire design in one effort. This segmentation can be implemented in various ways. By key function (group), by key subsystem, or by domain are typical approaches, Figure 1. Performance and cost targets are set for each partition. Once the design team is confident that each partitioned solution will meet performance the system is re-integrated (if applicable) then deployed.

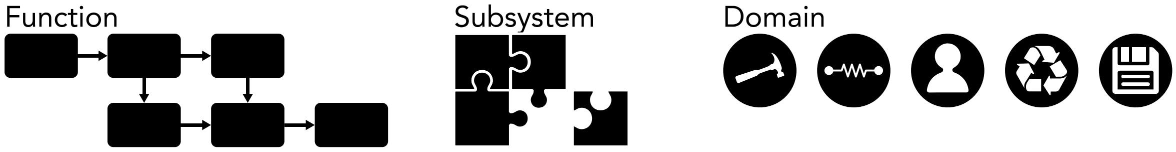


Figure 1: Partitioning of a system, there are numerous approaches to partitioning a complex system. Three common approaches are either by function, subsystem, or domain.

3 SEARCH TECHNIQUES

There are two core techniques for searching the design space of solutions for each partition of the design problem, via testing with prototypes. These involves either the iterative, temporally sequential, testing of overlapping design concepts, or the parallel testing of multiple concepts at a single point in time (Dahan and Mendelson 2001, Thomke and Bell 2001). Other strategies have been presented (Hannah *et al.* 2008, da Silva and Kaminski 2016), there work herein helps to quantify differences and to explore how single prototypes fit in a larger problem scheme.

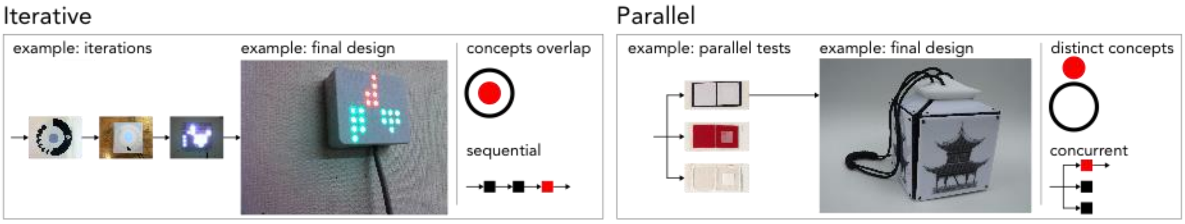


Figure 2: The most common techniques for searching a design space are iteration (left) and parallel testing (right)

Expanding work from (Bradley Adam Camburn *et al.* 2015) we extract empirically a new model of the effect of iterative testing on performance. Based on additional data from the empirical study of a design challenge, reported in this previous work. We also extract a new model of the impact of parallel testing on performance. A key insight is the distinct difference between the gradual performance increase of iteration and the discontinuous performance leaps associated with parallel concept testing. Equations 1 and 2, below, depict the expected performance of iteration and parallel testing.

$$\Pi \propto \Pi_0 e^{\Delta \cdot n} \tag{1}$$

where Π is design performance, Π_0 is the initial performance, n is the number of iterations on a single concept, Δ is the gradient of the local design space

$$\Pi \propto \max_{i \in m}[\Pi_i] \tag{2}$$

where Π is design performance, Π_i is the performance of a concept i, m is the set of distinct design concepts tested.

Figure 3, below, visually depicts the performance results of iteration and parallel testing from the results of the experiment reported in previous work (Bradley Adam Camburn *et al.* 2015). An exponential equation of best fit, to the iteration performance results, had the highest R^2 value as compared to linear, or polynomial equation fitting results ($R^2 = 0.91$) computed using all test data in the given study. These results reiterate the critical insight that parallel prototyping allows for large, discontinuous leaps in performance. The sample data was taken from a study in which participants produced a simple transport mechanism. Performance is measured by distance.

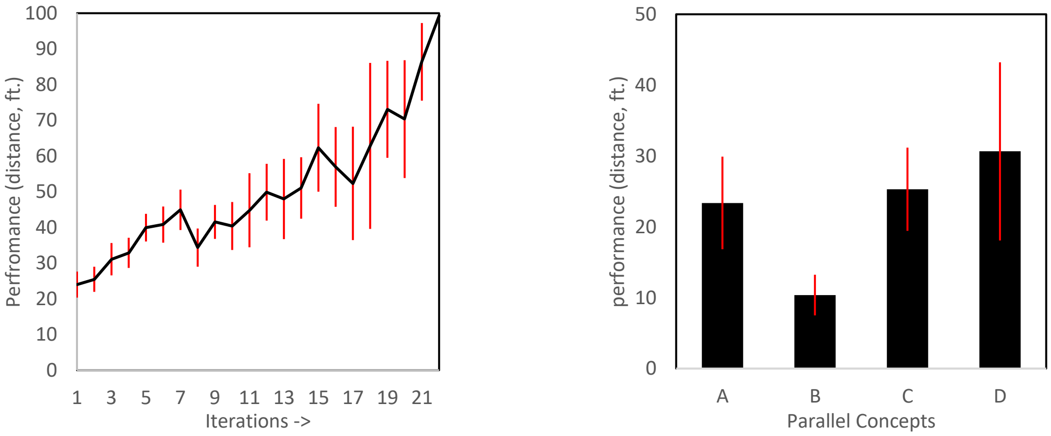


Figure 3: Empirical data for iteration versus parallel testing, performance effects. Values are averaged across all teams. For the parallel concepts, values are average for the first test only. +/- 1 standard error shown.

Consider the following example. If a hypothetical team applied parallel testing of four different concepts, then they will roughly achieve a performance of 31 ft. Conversely, if the design team chose a single concept and constructed four iterations, the performance could be as high as 38 ft. or as low as 12 ft., depending on which concept was chosen initially. This exercise highlights the risk of an iterative single-concept testing strategy. Note that, these given numerical values are one example only. The constants of performance likely vary by context. Qualitative observation of these experiments suggests that when an ineffective concept is chosen, multiple iterations will not recover performance until a new concept is adopted.

Table 1: Example equations for performance (units are of distance, d, in this case measured in feet) using iteration, and parallel testing data.

Iteration	$\Pi(\mathrm{d}) = \Pi_0 \mathrm{e}^{0.05*\mathrm{n}}$
Parallel	$\Pi(\mathrm{d}) = \max[21, 10, 25, 31]$

4 IMPLEMENTATION TECHNIQUES

There are numerous prototyping strategies that can be applied to reduce cost (Gordon and Bieman 1995, Buchenau and Suri 2000, Moe *et al.* 2004, Dutson and Wood 2005, Drezner and Huang 2009, Bradley Camburn *et al.* 2015). Herein, key techniques have ben synthesized to form three conceptually distinct cost reduction techniques. These are *scaling*, the reduction of cost by reducing the size or functional order of a design; *isolation*, the selection of a particular key subsystem to be prototyped, in isolation from the rest of the system; and *abstraction*, the representation of a meta-function without consideration of internal functionality.

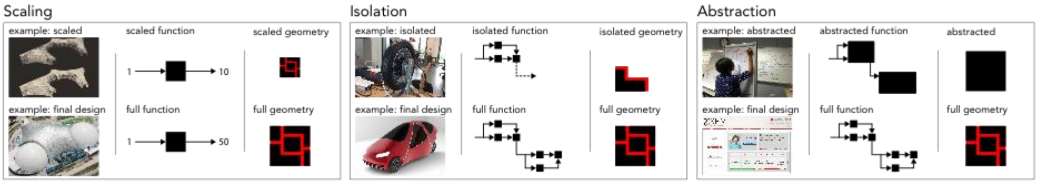


Figure 4: Three core techniques for implementing a single prototype test embodiment are scaling (left), isolation (middle), and abstraction (right).

Equation 3, which is based on expanded analysis from (Bradley Adam Camburn *et al.* 2015), demonstrates that these three techniques result in a co-operative, proportional reduction of prototype cost.

$$\mathbb{C}_r \propto \frac{\mathbb{C}}{S_c \cdot I_s \cdot A_b} \tag{3}$$

where $\mathbb{C}$ is the full system cost, $\mathbb{C}_r$ is the reduced implementation cost of a prototype, and S_c is the scaling factor I_s is the isolation factor A_b is the abstraction factor.

A key insight is that multiple techniques can be applied and the cost of a prototype can be radically reduced. Hybrid techniques reduce cost of the overall prototyping effort. They enable a greater number of iterations or parallel tests. Figure 5 graphically depicts the interaction of scaling and isolation quantitatively. The results are based on empirical data from (Bradley Adam Camburn *et al.* 2015). The empirical data fits this equation closely, (R^2 value > 0.9) based on the given data set. Exact values for the constants are to be considered with caution as they are likely highly dependent on the specific design task, they are reported in Table 2 for completeness.

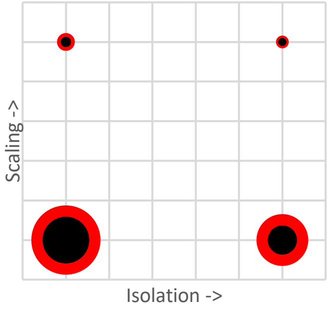


Figure 5: Average prototype cost given scaling versus isolation. Area of bubble is proportional to average cost of prototypes in that category across all teams (e.g. 0,0 is a full prototype, 1,1 is a scaled and isolated subsystem). Red outline shows +1 standard deviation.

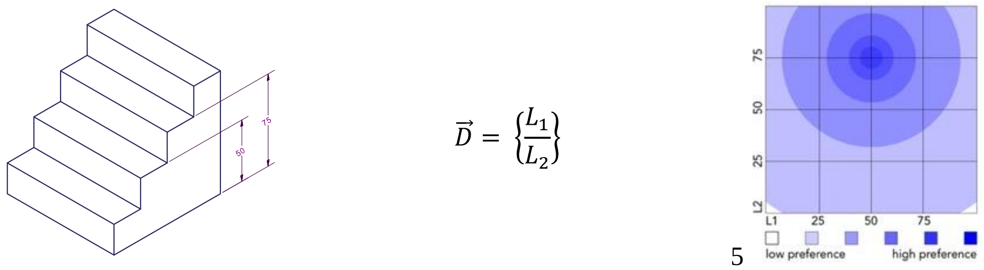
The impact factors also seem intuitive; as abstracted models can be extremely low fidelity (e.g. a folded piece of paper). Conversely, an isolated prototype is typically of near full functional and may only result in a marginal cost reduction.

Table 2: Sample factors values extracted

Abstraction, Ab	7.4
Scaling, Sc	3.2
Isolation, Is	1.6

5 SEARCH STRATEGIES

When designers develop new products, services, and systems they may often employ complex search strategies that cannot be simply captured with the terms ‘iteration’ and ‘parallel testing’ as they are a of multiple techniques. This section explores the parameterization of designs into a topological vector space (Figure 6), and how this may aid in the visualization and analysis of complex prototyping strategies. A prototyping strategy can be seen as a search effort in a topological space (Figure 7). In reality, actual design spaces may contain hundreds of variables and be impractical to model in this manner. The example is given for visualistion. A prototyping effort can be represented as in (Figure 8) with simplified maps showing the testing sequence. The wireframe strategy is presented in case studies below as it is infeasible to represent complex spaces graphically. This kind of segmentation is common in set-based design (Schäfer and Sorensen 2010, Yannou *et al.* 2013). This approach helps to visualize the impact of lean strategies (Ward *et al.* 1995, Ward and Sobek II 2014), and complements such approaches by highlighting a critical inter-relationship of parallel designs. They allow the team to map a design space, i.e. reduce local uncertainty accumulatively.



$$\vec{D} = \begin{Bmatrix} L_1 \\ L_2 \end{Bmatrix}$$

Figure 6: Illustration on parametric design model of staircase. (left) simple staircase of two steps between the landings. (center) parametric representation of the design, L_1 is the first step height, L_2 is the second step height. (right) Topological map to visualize user preference

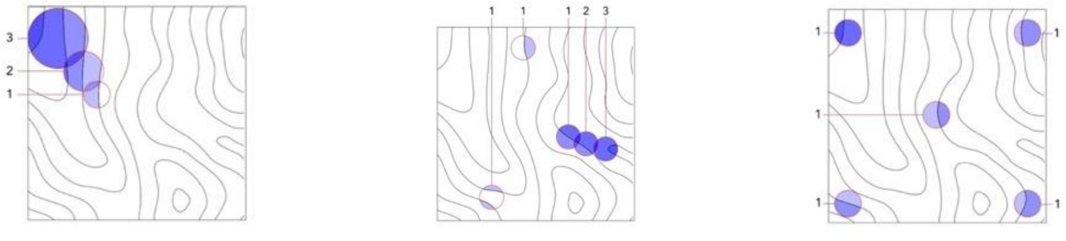


Figure 7: Figurative representation of hypothetical prototyping strategies. Numbers indicate test sequence. (left) ‘Proof-of-Concept, Alpha, Beta’ testing. (center) mixed strategy (right) multiple, diverse, low fidelity parallel tests.

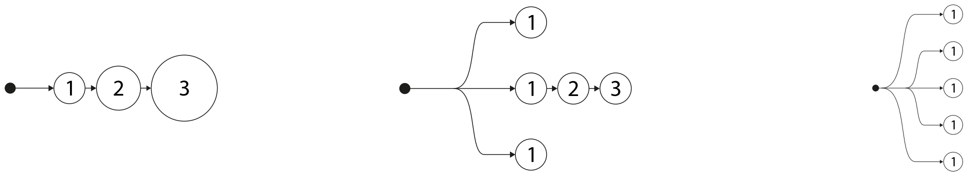


Figure 8: Simplification of the strategies shown in Figure 8, (left) ‘Proof-of-Concept, Alpha, Beta’ testing. (center) A mixed strategy. (right) Parallel tests.

Search strategies have a direct relationship with cost and performance. As depicted in Figures 7 and 8 a higher fidelity model allows for clearer understanding of the design performance in the local space, but this information comes at a higher cost. By contrast, low fidelity models afford less information about the local design space, but may be critical in understanding global design space topology. As a key insight for designers, higher fidelity models should come later in design efforts to reduce overall cost, once the global performance topology is better understood. In summary, to maximize value (Equation 4), or the ratio of final performance to total cost, it is beneficial to explore many conceptually diverse low fidelity prototypes early in the design effort.

$$V \propto \frac{\max_{\mathrm{i,j} \in \mathrm{n,m}}[\Pi_{i,j}]}{\sum_{i,j=1}^{n,m} \frac{\mathbb{C}_i}{[S_c \cdot I_S \cdot A_b]_{i,j}}} \tag{4}$$

where V is the value of a prototyping effort, $\Pi_{i,j}$ is the performance of iteration j of concept i. n is the number of iterations (of each concept) and m is the set of concepts, $\mathbb{C}_i$ is the cost of a full system of concept i, and $[S_c \cdot I_s \cdot A_b]_{i,j}$ is the reduction factor for each iteration j of each concept i

The above modeling approach can clearly capture traditional approaches such as ‘proof of concept’, ‘alpha’, and ‘beta’ (Figures 7 & 8 - left). It also could be used to understand why hackathons are effective in rapid solution development, as participants often rapidly produce many distinct low-fidelity prototypes to explore a wide space. This modeling approach extends previous work by the authors and extends this perspective of prototyping to incorporate systems development.

6 CASE STUDY: MEDICAL CENTRE

To evaluate the effectiveness of the proposed modeling approach a service case study is supplied. The design effort was partitioned by function (Figure 9). We report the strategy employed for two key system functions. Service prototyping is a well-explored research topic (Passera *et al.* 2012). This work aims to demonstrate that a similar core approach can be applicable to both service and system design prototyping. The design team was working to redesign a series of working service centers for improved user experience.

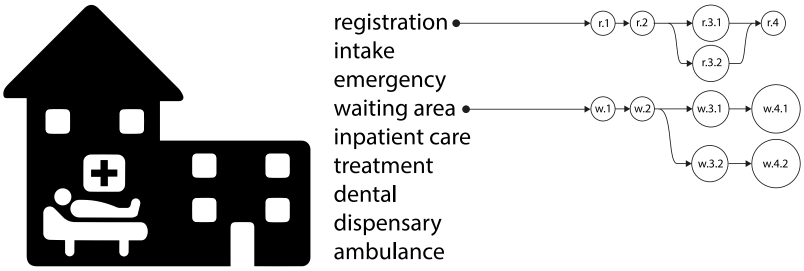


Figure 9: Overview of medical center system prototyping strategy, partitioned by function.

One key function was to provide visitors with a mechanism to reduce front-end loading at reception. The design solution was a pre-registration app. A series of iterations and low fidelity parallel tests were employed. Note, each prototype shown in Figures 10 and 11 is coded to the overall strategy map provided in Figure 9.

r.1: initial pre-screening concept

r.2: app and control station detail

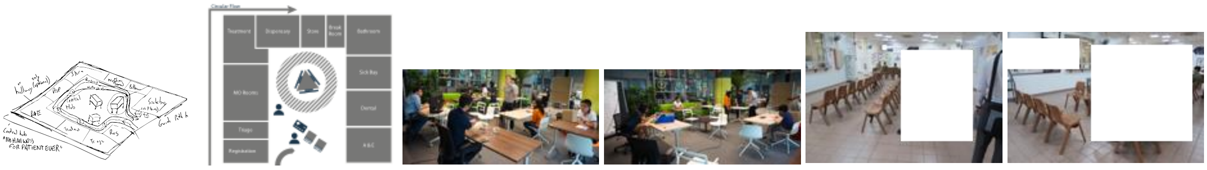
r.3.1: user testing, interface one

r.3.2: user testing, interface two

r.4: low fidelity paper prototypes, final app

Figure 10: Search strategy for patient registration function.

The relationship between perceived service quality and the waiting area layout was also explored. Numerous mockup prototypes supported the overall service prototype as well as scenario action cards for participants. The final prototyping effort involved deploying a prototype in the facility itself. A key insight of this effort was to discover the difficulty of way-finding in the facility through low-cost user testing. This insight was not initially reported by users, and allowed for valuable design enhancements. Notice that the effort includes a mixture of parallel and iterative testing with gradually higher fidelity.



w.1: initial layout concept | w.2: detailed layout concept | w.3.1: first layout, mockup | w.3.2: second layout, mockup | w.4.1: first layout, user test | w.4.2: second layout, user test

Figure 11: Search strategy for waiting area function.

7 CASE STUDY: HYBRID PROPULSION SYSTEM

A second case study is the development of a launch vehicle using hybrid propulsion. This complex system requires numerous prototypes and is sequentially partitioned by domain, then subsystem, and again by domain (Figure 12). The prototyping strategies for several key subsystems are reported. In this case, the design team was working to develop a custom additive manufacturing capability.

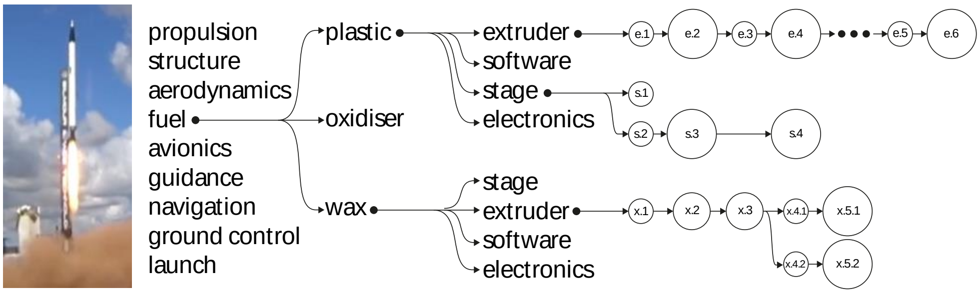


Figure 12: Overview of hybrid propulsion system prototyping strategy, partitioned by subsystem and then by domain. We report the strategies employed for a small subset of the critical fuel generation system.

One of the most critical systems in this launch system was a multi-material 3D printer. This printer produces a key component of the engines and is not available commercially. Figure 13 depicts a sequential design and testing strategy for the Fused-Deposition-Modeling (FDM) extruder head, which is a key subsystem. The alternating use of low cost CAD models, and high fidelity physical models allows for reduced cost. There were nearly twenty iterations of the extruder, three are shown.

e.1: initial design, CAD | e.2: initial design, functional | e.3: mid-point design, CAD | e.4: mid-point design, functional | e.5: final design, CAD | e.6: final design

test results ->

failed print | structural warp | improved print | thermal analysis | final print

Figure 13: Search strategy for FDM extruder sub-function

Figure 14 shows prototypes from another key subsystem, the X-Y-Z motion stage. Two radically distinct stage concepts were compared using low fidelity models before iterating on a higher fidelity model of the chosen stage type.

s.1: H bridge XY stage mockup

s.2: stacked XY stage

s.3: 2-rod z axis, integrated stage

s.4: 3-rod z axis, final stage design

Figure 14: Search strategy for FDM x-y-z motion stage

Figure 15 highlights prototypes from the secondary emulsion extrusion system. Since this was a relatively new concept, several low fidelity tests were employed to evaluate the design space. These allowed the designers to identify the valve as a critical subsystem. Two competing valve designs were developed and tested in CAD and then in physical prototypes before the simpler butterfly valve design was selected.

x.1: material characterization

x.2: tube flow characterization

x.3 scale extruder model

x.4.1: ball valve design CAD

x.5.1: ball valve physical test

x.4.2: butterfly valve design CAD

x.5.1: butterfly valve physical test

Figure 15: Search Strategy for emulsion extruder sub function

Figure 16 shows the final, integrated, system design alongside a sample multi-material print. This print sample will be employed in the launch system. It is critical to note that only a demonstrative subset of the total prototyping effort has been shown here to highlight several exemplar strategies. It is critical that a system prototyping effort include each subsystem at some level of testing, or there may be unexpected behaviors in the final design.

Figure 16: Integrated multi-phase engine printer. (left) Final system CAD. (right) Final system physical construction.

8 DISCUSSION

The paper presents a number of observations on the relationship of prototyping techniques (iteration, parallel testing, scaling, isolation, and abstraction) in the form of representative equations. The provides an initial response to the first research question, *"What are the relationships between prototyping techniques, cost, and performance?"*

A simple graphical representation of a sample design is given, and used to illustrate prototyping strategies. This map example is then revised as a simplified linear model for compact representation of prototyping strategies. This provides preliminary response to the second research question, *"Can traditional (and more complex) prototyping strategies be viewed in a graphical way?"*

Finally, two case studies are supplied in which the given tool is used to help build a relationship between a large number of prototypes explored in these exemple design efforts. This provides a first answer to the third research question 3, *"Is the given mapping approach applicable to both service and system prototyping efforts?"*

These results open additional questions for future consideration. The following observation is made, higher fidelity prototypes allow for better insight into the design performance in the local space, but capturing this information is costly. In contrast, low fidelity prototypes provide less information on the performance in the local design space but the global design space topology is widely explored. We may draw analogies to searching the hypothetically depicted spaces and formal search algorithms.

Design of experiments literature provides insight into potentially innovative design prototyping search strategies to handle this tradeoff between information cost and value in the context of engineered systems. Established, quantitative search strategies that typically rely on a well-established set of design and response variables (e.g., Latin hypercube sampling), could be adapted to more holistic design concept testing. In such methods iterative experiment informs the next experiment such that information value per trial is high. Computational search algorithms also balance this tradeoff. For example, simulated annealing (Kirkpatrick 1984) places a high value on divergent solutions. It begins with a high probability of accepting a divergent solution and decreases this probability as the number of iterations increases. For example, rather than directly iterating the design team may explore many distinct low fidelity concepts early on and then converge toward a series of higher fidelity directed tests around a well-performing concept. This is well matched to the concept of Lean manufacturing that encourages extensive information gathering early on in the design process (Ward *et al.* 1995). Particle swarm optimization uses many simultaneous agents that share information to guide search locally and globally, this for example may also be analogous to hackathons in which multiple agents explore the design space using many low fidelity design prototypes. Again it is easy to visualize this strategy using the given visual approach.

One risk of low fidelity prototyping is that the design team may walk past a so-called "activity cliff". These are regions of sharp sudden gradient in performance. A recurrent observation in drug design studies. Wherein small changes in chemical structure lead to large discontinuities in activity or other properties. These discontinuities introduce challenges in predicting how changes to a drug's structure will alter its behavior. A variety of techniques have been developed to detect these discontinuities in order to produce a mapping between the structure and behavior spaces (Stumpfe *et al.* 2013) including random forests (Guha 2012) support vector machines (Heikamp *et al.* 2012), and particle swarm optimization (Namasivayam and Bajorath 2012). Future work could explore engaging such methods with prototypes to identify activity cliffs. However, the challenges of directly adapting search algorithms is that the design variables may be inherently unknown. This means that quantitative search strategies are only applicable by analogy. In summary, there is an opportunity to draw analogies to other means of searching design spaces and adapt them to the current approach. Prototyping is a framework into which many potential search strategies can be injected.

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