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EVALUATION OF A STRATEGIC METHOD TO IMPROVE PROTOTYPE PERFORMANCE WITH REDUCED COST AND FABRICATION TIME

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Abstract

Prototyping is tied into many stages of product development, where implementation choices have critical effects on overall design outcome. We review six techniques for strategic prototyping and synthesize empirically derived heuristics for their application. The heuristics are integrated in a generalized method for strategic prototyping. Two complementary experiments are conducted to evaluate each technique, as well as one potential form of the method. Direct performance measurement quantifies the continued marginal performance increases associated with iteration (build and test cycle of a single concept), and the benefit of pursuing multiple design concepts. Results also show scaled prototyping, subsystem isolation, requirement relaxation, and virtual prototyping can reduce cost and fabrication time. The method is correlated with increased use of these techniques, and higher quantitative final performance. The strategy method is a broad planning tool that leads to improvement of final design performance and reducted fabrication cost and time. Potential areas for improvement are evaluation of: marginal benefits from many parallel concept tests, and alternate method layouts.

Keywords: Design methods, Early design phases, Product modelling, models, Prototyping

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1 INTRODUCTION

Prototyping is a key activity for both convergence (validation) and divergence (exploration) in a design space (Reed Doke 1990, Lim et al. 2008, Lennings et al. 2000, Moe et al. 2004). To develop a prototype, the design problem must be partitioned (Gero 1990). In this context, partitioning means selecting a subspace for testing. The specific objectives of this partitioning must be decided (Otto and Wood 2001, Drezner 1992). This reflective interaction is essential to forming a constructive view of the design space (Schön 1992). Physical models help clarify requirements (Gordon and Bieman 1995), and identify potential avenues for performance increase (Viswanathan 2012). This process can improve design decision making (Drezner 1992).

Of critical note, sensitivity analysis identifies prototyping as a driver of design outcome (Badri et al. 1997). Further empirical evidence shows that a chosen approach to prototyping impacts these outcomes (Thomke 1998). However, there is an inconsistent success rate in product development (Badri et al. 1997). Prototyping strategies are often developed in an *ad hoc* manner, and may contribute to that inconsistency. These observations highlight the criticality of strategic prototyping (Riek 2001). Empirical techniques must be defined and validated to promote the reproducibility of successful outcomes (Krishnan and Ulrich 2001).

This study explores prototyping for the development and testing of new electro-mechanical products or systems designs. A strategic method is proposed that is inspired by previous research (Camburn et al. 2013), with refined heuristics synthesized from empirical research. The objective of this method is to improve the performance outcome of a prototyping effort while also reducing expense of time and other resources. The method provides a guide to implement six strategy variables, each of which defines a range of possible choices for implementing a prototype (such as the number of iterations, or physical scale). Refer to Figure 1. These choices include the number of prototypes to be explored, and the implementation characteristics of each build. Accordingly, the method provides a way to navigate this space. Detailed description of the techniques follows. Furthermore, novel empirical results regarding the outcome-effects of the specific techniques are provided.

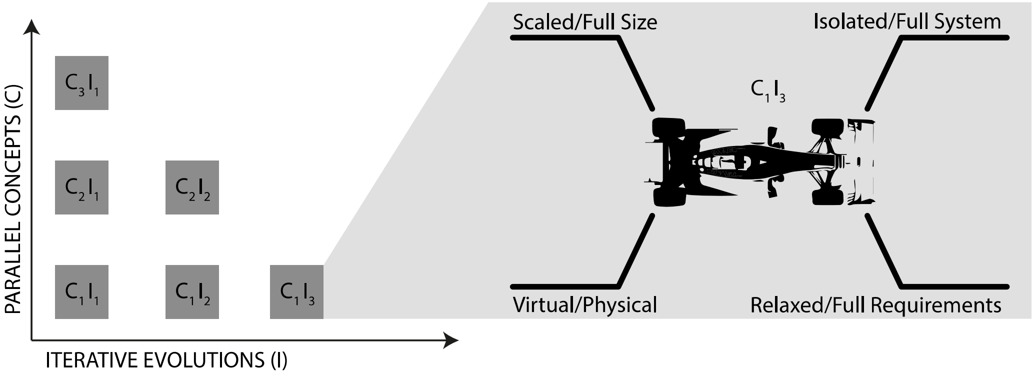

Figure 1. Expanded-dimensional space of a prototyping strategy. A strategy may consist of several concepts, and multiple iterations, each with unique implementation characteristics.

1.1 Review of Techniques for Direct Performance Increase

This section will cover two techniques that when employed, typically result in increased final performance.

Iteration

Iteration is the sequential testing and refinement of a prototype. Refer to Figure 2. It is reported as a key strategy element [61], and allows systematic advancement towards a mature design (Drezner and Huang 2009). Iteration is critical to identifying errors and simplifying parts (Zemke 2012). Empirical studies have shown that teams in an iterative design condition significantly outperform teams without iteration, for reported self efficacy as well as direct performance measures (Dow et al. 2009). However, as Thomke observes from an industry case study (Thomke 1998), and Viswanathan from a controlled empirical study (Viswanathan 2012), fabrication methods can affect the number of iterations pursued (with more complicated fabrication leading to fewer iterations). One approach for planning the number of iterations is roughly estimated from the ratio of potential performance increase value, to expected testing cost (Thomke and Bell 2001). A similar alternative estimates iteration number from the ratio of total available time to the expected time required to test each iteration (Glegg 1981). These approaches help ensure that the strategy for iteration will not exceed the project budget.

Parallel Prototyping

Parallel prototyping, is the fabrication and comparison of multiple design concepts in parallel. Refer to Figure 2. Parallel prototyping provides critical feedback for concept selection (Christie et al. 2012). This feedback may occur at the system or subsystem level (Gero 1990). Observations from industry identify that concurrent development enhances outcome (Badri et al. 1997). However, strategy selection has implications to cost and time expenditure (Ulrich 2000). Parallel prototyping has demonstrated value in a time-constrained environment, with several apparently equal design concepts e.g. as evaluated by Pugh chart (Riek 2001). However, the integration of information across efforts is critical (Thomke 2003). Empirical studies support that teams pursuing parallel testing achieve greater performance and diversity than groups with only a single design, or several iterations (Dow et al. 2010, Dow et al. 2012, Neeley Jr et al. 2013). Teams that develop parallel prototypes may perceive an increased time constraint (Neeley Jr et al. 2013, Camburn et al. 2013). One high level guide is to employ parallel prototyping when budget is flexible (Moe et al. 2004). Specifically, Riek proposed that the number of concepts to test may be given by the ratio of budget to expected prototyping cost (Riek 2001). An alternative is given by Dahan as the ratio of profit uncertainty to the cost of each prototype (Dahan and Mendelson 2001).

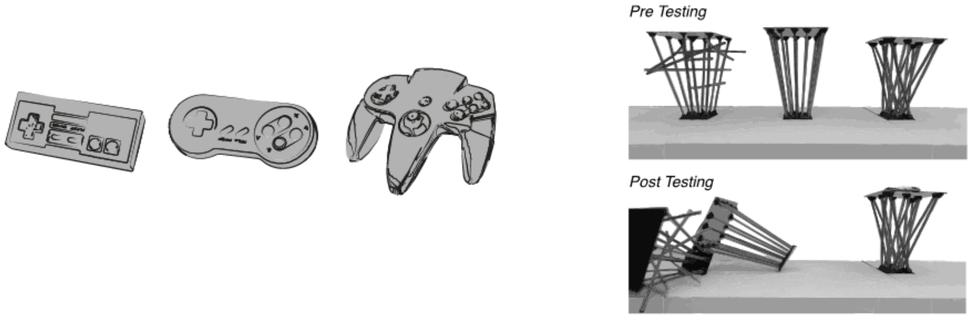

Figure 2. Performance increase techniques (left to right) iterative design, parallel testing

1.2 Review of Techniques for Cost and Effort Reduction

This section will cover four techniques that typically increase the feasibility of a prototyping effort by reducing cost and/or time required for development.

Scaling

A scaled prototype mimics behaviour(s) of a larger (or smaller) design through similitude. Refer to Figure 3. Similitude, discovered in the 19th century, enabled the production of accurate scaled models (Kempf 1940). This method was advanced by Naval designers in the mid 20th century (Kempf 1940). Scaling can be employed to reduce cost (Otto and Wood 2001), or enhance feasibility of testing a prototype (Christie et al. 2012). With the advent of advanced computer modelling, scaled virtual models can include incredibly dense design information, ultimately leading to more complex designs (Mitchell 2004). One method, empirical similitude, involves independently scaling several parameters of the system in parallel to form an integrated, vectorized model with very high accuracy (Cho et al. 1998). In-situ observation identifies that is it critical to scale loads accordingly (Viswanathan 2012). To strategically execute scaling, methods suggest evaluating feasibility of the full design before scaling (Moe et al. 2004, Christie et al. 2012).

Isolated Subsystem Testing

An isolated subsystem prototype, is a segmented build for a single subsystem (or group of subsystems) explored in isolation. Refer to Figure 3. System segmentation can permit rapid exploration of different aspects of the design (Horváth and Bois 2012). Dod studies show that subsystem isolation result in lowered costs and reduced uncertainty (Drezner and Huang 2009). Isolated subsystem prototypes can make it easier to demonstrate one function (Horváth and Bois 2012). It may be difficult to address unanticipated needs with this approach (Rogers et al. 2013). The strategic approach of each subsystem may vary (Christie et al. 2012, Yan et al. 2002). For instance, they may be a mixture of physical, virtual (Yan et al. 2002), or scaled models (Faithfull et al. 2001). However, effective re-integration is critical. It is possible to pseudo-connect the isolated models; analogous to a network (Yan et al. 2002). This technique is suggested especially in evolutionary design where the upgrade is primarily concentrated in one subsystem (Christie et al. 2012).

Relaxed Requirement Prototypes

A relaxed requirement prototype, is a prototype wherein functionality may be evaluated with less stringency than necessary for the final requirements. Refer to Figure 3. Low fidelity prototyping facilitates forward movement (Kelley 2001, Gerber and Carroll 2012) concept level discussion, (Wong 1992), and reduced cost (Otto and Wood 2001). This in turn also enables evaluation of multiple concepts (Thomke and Bell 2001) at a rapid pace (Drezner and Huang 2009). Low fidelity prototypes are critical in simulating usage (Buchenau and Suri 2000). They are more holistic than other approaches (Blomkvist and Holmlid 2010). The DoD identifies that this approach is essential for early risk reduction, and requirement refinement (Drezner and Huang 2009). Though they may be inaccurate, they can be practical because of the tradeoff between accuracy and cost (Otto and Wood 2001). Since even a fully functional prototype may misrepresent features (Little 2003), the test environment must be realistic (Drezner and Huang 2009). Reduced requirement prototyping is also suggested when a full system may be infeasible given fabrication capabilities in context (Sefelin et al. 2003). Adjustment of the requirements should be executed with careful consideration (Christie et al. 2012, Otto and Wood 2001). Evaluation of the importance of specific design requirements (possibly from QFD) should play a role in decisions related to design requirement relaxation.

Virtual Prototyping

A virtual prototype, is a model constructed on a computational platform that simulates an aspect of a physical design. Refer to Figure 3. Virtual models can contain complex topology (Mitchell 2004), and provide easy access to test data that might be challenging to measure otherwise (Spinoff 2008). Examples are fatigue data, or risk assessment of logistical problems such as process modelling of bridge construction. These benefits may be summarized under the ability of virtual prototyping to synthesize design and testing (Wang 2002). Virtual models also permit integration of design and manufacture (Sghaier and Soriano 2008), algorithmic design through formalisms (Shea and Cagan 1999), or simultaneous demonstrations in multiple locations (Cugini et al. 2008). Empirical studies demonstrate cases where virtual modelling is faster (Hammon et al. 2014), performs equally (Wojtczuk and Bonnardel 2010), required less effort (Riek 2001), and provided more flexibility, compared to physical models (Sefelin et al. 2003). A study found material quality was not perceptible from virtual models (Dahan and Srinivasan 2000). Virtual modelling tool interfaces may be non-intuitive (Wojtczuk and Bonnardel 2010). Virtual models can only simulate phenomena that are directly encoded (Riek 2001). One approach is to select between physical and virtual models based on the ratio of effort to accuracy (Otto and Wood 2001). Another method suggests strategic identification of desired results (Christie et al. 2012).

Figure 3. (left to right) scaled prototype (architectural), isolated subsystem (simple joints), relaxed requirement (paper mockup), virtual prototype (chair aesthetic design)

2 INTEGRATED PROTOTYPING STRATEGY METHOD

The literature was carefully evaluated, and critical empirical evidence summarized. This foundation is used in the strategy method (Figure 4) to identify design contexts likely to benefit from a particular technique. Iteration and parallel prototyping directly lead to performance increase. In a complementary fashion, scaling, subsystem isolation, requirement relaxation, and virtual prototyping can reduce time and cost expenditure without performance loss. Thus, it may be feasible to implement a performance enhancing strategy, even in cases of limited resources. The method presents one potential synthesis architecture, however there are alternatives that may be equally valid such as analytical models, flash cards depicting techniques, or a prototype planning notebook. The goals are to encourage systematic prototyping, and to expand the prototyping space to a larger dimensionality (in this case 6^n) rather than a traditional stage-gate approach of proof of concept, alpha, then beta level prototyping.

Furthermore, this synthesis of the empirically founded heuristics is designed to directly incorporate general design contexts. This version of the method is presented as a set of six techniques, each with several heuristics to guide implementation of the specific technique. The designer may provide a Likert response to each heuristic and take the average under a specific technique to identify a strategy for that technique. The magnitude of the average helps to identify the potential applicability of that specific technique. If a neutral response is identified, the designer may re-assess each heuristic to establish preferred direction. This combination approach allows for simultaneous consideration of the potentially competing heuristics. Furthermore, reviewing the heuristics in a single matrix may present significant time savings compared to trial and error learning approaches.

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.					

Figure 4. Integrated strategy method, which employs a direct synthesis of the heuristics for each technique to provide a prototyping strategy planning tool.

3 DESIGN EXPERIMENTS

Two complementary experiments provide an opportunity to investigate the techniques and method. The experiments are similar, with variation in duration and design problem to permit a broader understanding of effects. One focuses on a short term, design challenge, and the other a long-term *in-situ* study. The design challenge study helps to examine and compare direct performance; with multiple teams working on the same problem. The *in-situ* study provides results regarding budget and time expenditure; teams approach varied design problems, allowing broader evaluation of the method.

Note that the participant pools of each experiment were exclusive. The participants were a random mixture of male and female junior and senior university students in mechanical engineering or industrial design. Participation was voluntary.

3.1 Design Challenge

The controlled study permits direct performance measure quantifications. The performance objective was variable and has no practical upper limit. Refer to Figure 5. Teams were required to construct a device that uses potential energy to move a piece of paper, as far as possible down a hallway. Each team was given a set materials kit. A researcher manually recorded elapsed time for each test with a stopwatch and distance travelled in each test using a tape measure. The specific requirements of the design objective, and an example solution are shown in Figure 5. Teams were required to start within a given boundary. Teams were given 15 minutes of instruction, followed by 5 minutes of free ideation (control) or exposure to the strategy method (experimental), and finally 50 minutes of build and test time. There were 64 participants in this study, equally divided between experimental and control groups. Participants completed the design problem in teams of two persons.

3.2 In-Situ Study

For the *in*-situ study, teams in a senior mechanical engineering capstone design course were provided with the method and materials via a lecture at the outset of the semester. This study, in particular, permits analysis of budget, and time expenditure. The projects are industry sponsored and teams often develop fully functional prototypes (Figure 5). Solutions range from offshore mining components, to medical equipment. This study permitted a long term exploration of the strategy, as well as evaluation over a wide range of design problem types. For this study, researchers interviewed each team individually, after 3 months of prototyping time to determine: budget for each prototype (in USD), time to build each prototype, use of scaling, subsystem isolation, requirement relaxation, and virtual prototyping. This study had 105 participants, who completed the design projects in teams of 3 to 5 individuals.

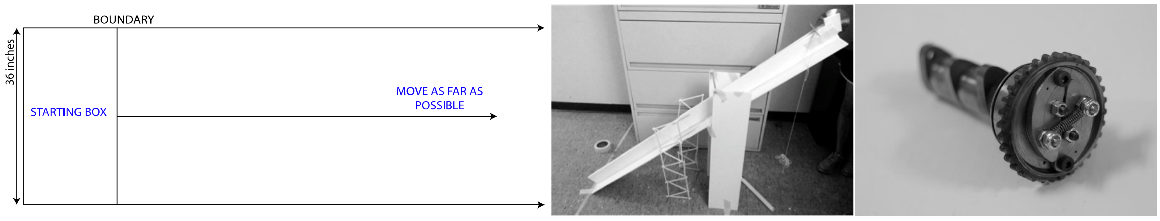

Figure 5. (left to right) design challenge layout, example solution (design challenge), example solution - cam phaser (in-situ)

4 EXAMINATION OF RESULTS

This section explores results from the two experiments described in the previous section. First, individual techniques are evaluated. Then, the effect on performance of the integrated method is shown.

To establish significance of testing, the Student's t-test is used in cases of variable mean, where any *p-value* less than 0.05 is considered sufficient to reject the null hypothesis. Correspondingly, test of two proportions is employed for instances of binomial distribution (using a transformed z-test), wherein any *p-value* less than 0.05 is also taken as sufficient to reject the null hypothesis.

4.1 Results for Individual Techniques

Iteration

These results, from the design challenge, are first to report the marginal effects of continued cycles of iteration (Figure 6). Performance continues to increase up to 400% of the initial distance score, with an average performance increase of 12% per cycle. The r^2 value of linear regression of the results is 0.85.

Fabrication time with respect to iteration is also reported for the first time. Observations show a remarkable complement to performance results, with a decreasing fabrication time over continued iteration. There was a significant drop after the first build, and after that a gradual reduction in the fabrication time for each build of about 8% per cycle. In a few outlying cases, the fabrication time suddenly increased. Observation notes connect these events to instances when a prototype failed critically and required significant repair time.

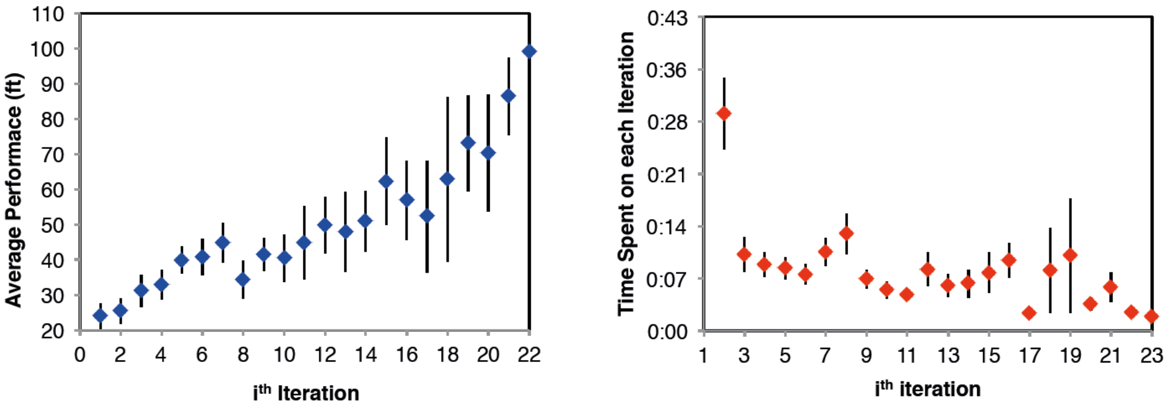

Figure 6. (left) performance over increasing cycles of iteration. (right) time to develop each iteration. ±1 standard error shown. Each point represents the average value (distance or time) of the i^{th} iteration, of all teams. Source: design challenge study.

Parallel Concepts

Exploration of a second concept resulted in a similar pattern. Performance of a second concept was greater than the first concept. The average distance reached by a team's second concept was 12.19 meters, while that of the first concept was only 5.79 meters. This difference is significant with Student's t-test at $p < 0.001$. Similarly, the first build of a second concept took significantly ($p = 0.04$) less time (12 minutes) than the very first build (30 minutes).

Interaction of Iteration and Parallel Testing

Comparative observation was made between iterative and parallel testing. Teams were given freedom to select their own strategy to emulate a realistic design scenario; therefore, a few terms are missing from the full factorial analysis. On average, teams introduced the second concept on the 3rd iteration. Interestingly, the average score of their first two iterations were significantly ($p = 0.05$) lower (5.79 m) than teams that only developed one concept (8.83 m). This suggests these teams identified a flaw in their first concept. Also, on average, the first iteration of a second concept took significantly ($p = 0.02$) less time (10 minutes) compared to the very first build (28 minutes). Thus, the time spent on the first build may be due to learning the context, more than implementing a specific design concept.

Scaling

Scaled prototyping was associated with a reduction in cost ($p = 0.003$). There was also a reduction in the time required to build each prototype, but not quite significantly ($p = 0.058$). Finally there was no significant loss of performance with scaled prototypes. See Figure 7.

Isolated Subsystem Testing

On average, isolated subsystem prototyping was associated with a reduction in time and cost; however, the difference was not fully significant ($p = 0.07$ for each); and there was no significant performance loss. There were a relatively small number of isolated subsystem tests in this study. Refer to Figure 7.

Requirement Relaxation

Requirement relaxation was on average associated with lower cost ($p = 0.01$) and time (t-test, $p < 0.001$) than for a full prototype. As expected, performance of the relaxed prototype was lower (t-test $p = 0.009$). Refer to Figure 7. The final performance (last prototype) of teams which fabricated at least one relaxed requirement prototype, was not significantly different than those that did not ($p = 0.38$).

Virtual Prototyping

Virtual prototyping was associated with a vast reduction of cost ($p = 0.005$). This is given in the context that modeling software was available. In other contexts this software may require purchase. There was no significant difference in time, and a slight increase in performance ($p = 0.009$). Refer to Figure 7.

Interaction of Scaling, Subsystem Isolation, Requirement Relaxation, and Virtual Prototyping

The possibility of testing for interaction effects between scaling, subsystem isolation, requirement relaxation, and virtual prototyping was evaluated. Due to the strategic freedom allotted to teams, only significant main effects could be studied and identified through the experiments.

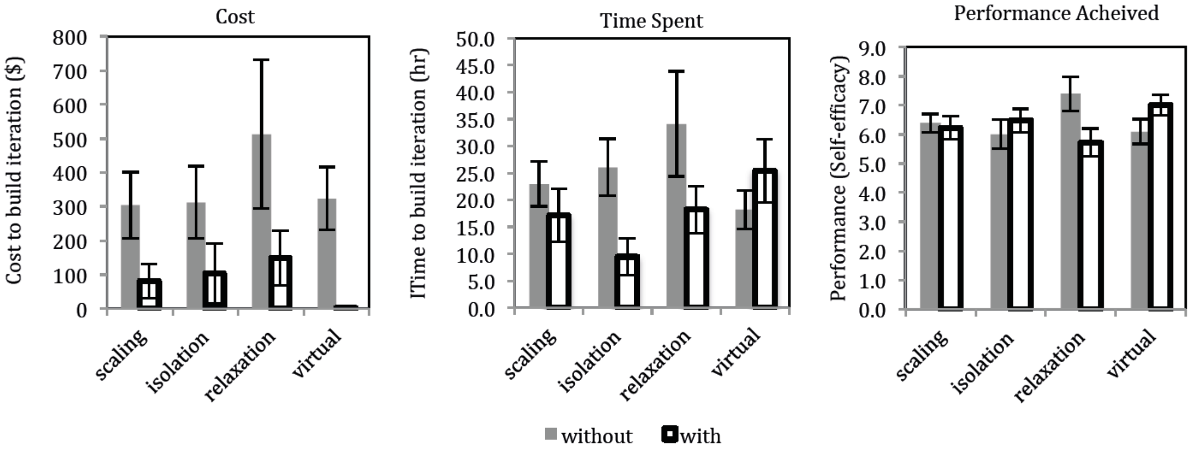

Figure 7. for each chart, (from left to right) cost, time spent, and performance achieved, the average scores are shown across all prototypes; the two bins above each technique represent the average either with or without the given technique ±1 standard error shown. Source is the in-situ study

4.2 Results for the Integrated Method

In the design challenge, experimental teams (exposed to the method) pursued more iterations (13) on average than the control group (9.3) with statistical significance ($p = 0.006$). The experimental teams explored more concepts (1.69), on average than the control teams (1.26) with statistical significance ($p = 0.005$). The experimental teams produced their first prototype in less time (19 minutes) compared to the control (41 minutes) on average, with statistical significance ($p = 0.014$). The experimental teams achieved greater performance on average (15.24 m) than the control (12.49 m) with statistical significance ($p = 0.018$).

Scaling, subsystem isolation, requirement relaxation, and virtual prototyping were assessed in the *in-situ study* by asking teams to self evaluate how closely they adhered or not to the strategy (Table 1). In cases where teams reported closely adhering to the strategy, implementation of all four variables was present in a significantly higher percentage of prototypes ($p < 0.05$) using the test of two proportions. Self efficacy results also indicated that high adherence was correlated with high overall performance.

Table 1. Use of scaling, subsystem isolation, requirement relaxation, and virtual prototyping (in-situ study), percentage of total prototypes with each technique, w.r.t. strategy adherence

Self reported adherence to strategy method	*Scaling*	*Subsystem Isolation*	*Requirement Relaxation*	*Virtual*
Low Adherence (1, 2)	33%	0%	50%	43%
High Adherence (4, 5)	54%	48%	86%	77%
p value	**0.0427**	**0.0001**	**0.0278**	**0.0176**

5 CONCLUDING REMARKS AND FUTURE VISION

Strategic prototyping can positively influence design outcome, but methodologies for implementation are fragmented. This study builds on a significant literature review with substantial empirical foundations for each of six heuristically guided specific prototyping techniques. These techniques are then integrated into a single context-independent prototyping strategy method. Finally, experimental evaluations of the techniques and method demonstrate their capability to increase performance, to reduce cost, and to reduce time expenses of prototyping.

Observations indicate that iteration directly leads to increased performance, and the marginal benefits of continued iteration are provided for the first time. Results also confirm the benefits of parallel prototyping, but instances of large numbers of design concept tests were not seen, so it was not possible to report the marginal benefits of parallel concepts. Furthermore, the results detail the effectiveness of scaling, subsystem isolation, requirement relaxation, and virtual prototyping to reduce cost and time required to develop a prototype, without loss of performance. Finally, it was observed that exposure to the method was associated with increased application of all six specific techniques, and overall performance increase.

To enhance generalizability, two experiments are pursued: a short term directed experiment in which all teams address a set problem; and an *in-situ* study in which each group approaches a different problem over a long time period. The results match previously reported empirical results in the literature review; which are in some cases drawn from larger industry studies. It is important to note that strategy must be pursued with inclusion of adaptive reasoning. The heuristics are a guide. It is important to pre-evaluate an approach's feasibility before implementation.

Potential future research may include alternative, formats for the strategy method or testing of hybrid techniques, e.g. relaxed requirement virtual prototype. Areas for improvement are expansion of data to include full factorial terms, and to corroborate the *in-situ* study results with a controlled study.

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