MIT Open Access Articles

The Economies and Dimensionality of Design Prototyping: Value, Time, Cost, and Fidelity

Massachusetts Institute of Technology

Edward Tiong
Ring Theory Pte. Ltd.,
6 Jalan Labu Manis,
Singapore 537991
e-mail: edward@ringtheory.com

Olivia Seow
Ring Theory Pte. Ltd.,
6 Jalan Labu Manis,
Singapore 537991
e-mail: olivia@ringtheory.com

Bradley Camburn
SUTD-MIT International Design Centre,
Singapore University of Technology and Design,
8 Somapah Road,
Singapore 487372
e-mail: bradley_camburn@sutd.edu.sg

Kenneth Teo
SUTD-MIT International Design Centre,
Singapore University of Technology and Design,
8 Somapah Road,
Singapore 487372
e-mail: kenneth_teo@sutd.edu.sg

Arlindo Silva
SUTD-MIT International Design Centre,
Singapore University of Technology and Design,
8 Somapah Road,
Singapore 487372
e-mail: arlindo_silva@sutd.edu.sg

Kristin L. Wood
SUTD-MIT International Design Centre,
Singapore University of Technology and Design,
8 Somapah Road,
Singapore 487372
e-mail: kristinwood@sutd.edu.sg

Daniel D. Jensen
SUTD-MIT International Design Centre,
Singapore University of Technology and Design,
8 Somapah Road,
Singapore 487372
e-mail: ddjensen7771@gmail.com

Maria C. Yang
Massachusetts Institute of Technology,
Cambridge, MA 02139
e-mail: mcyang@mit.edu

The Economies and Dimensionality of Design Prototyping: Value, Time, Cost, and Fidelity

Economic use of early-stage prototyping is of paramount importance to companies engaged in the development of innovative products, services, and systems because it directly impacts their bottom line. There is likewise a need to understand the dimensions, and lenses that make up an economic profile of prototypes. Yet, there is little reliable understanding of how resources expended and views of dimensionality across prototyping translate into value. To help practitioners, designers, and researchers leverage prototyping most economically, we seek to understand the tradeoff between design information gained through prototyping and the resources expended prototyping. We investigate this topic by conducting an inductive study on industry projects across disciplines and knowledge domains while collecting and analyzing empirical data on their prototype creation and test processes. Our research explores ways of quantifying prototyping value and reinforcing the asymptotic relationship between value and fidelity. Most intriguingly, the research reveals insightful heuristics that practitioners can exploit to generate high value from low and high fidelity prototypes alike. [DOI: 10.1115/1.4042337]

Motivation and Inspiration

Prototyping is a fundamental activity in the design and development of products, services, and systems [1–7]. In particular, physical prototyping is pointed out by practitioners as one of the most important and effective tools in their early concept work [8]. Large companies are not the only ones leveraging on the effectiveness of rapid and extensive prototyping to create revolutionary designs [9,10]. The building of prototypes has been ubiquitous in the development of innovative products, services, and systems across many industries, even with leaner and more agile companies and teams [1]; perhaps it is even more critical in lean environments where early validation of concepts is crucial [11]. One example is the development of a new payment device for children by SUTD-MIT IDC (Singapore University of Technology and Design—Massachusetts Institute of Technology International Design Center); the prototypes created—as seen in Fig. 1—served to amplify their designers' abilities and achieve high efficacy in such industry projects [12].

The applicability of prototyping to design practitioners has resulted in an increased academic interest in prototyping recently. Contributions include the role of prototypes in companies [3] and

state-of-the-art guidelines on prototyping [1,13], fast cycles of prototyping and testing to radically compress development time before making commitments, known as "sprints" [14].

Notwithstanding the above, there remain significant gaps in this field that compel us to investigate—especially in areas and from perspectives that will be pertinent and valuable to practitioners.

Existing studies tend to focus on student design teams in universities, which do not necessarily reflect the scale at which companies conduct their design processes in terms of cost, schedule, and performance [15]. These contributions often involve controlled experiments that, although produce undeniably reliable results, do not necessarily reflect the full spectrum of complexity that practitioners face in multidimensional industry problems [2]. In many cases, publications use anecdotal stories from industry practice to support their viewpoints rather than studies that systematically answer hypotheses. By doing so, these publications emphasize and underscore the need for more in-depth studies since the examples are used to illustrate rather than generalize [16–22].

All these point to a strong need for research around prototyping using data available from industry. Specifically, a realm of prototyping that greatly interests design practitioners is its economies. Prototyping in companies, unlike that in universities or research, directly affects the bottom line of a project [1,2]. As such, practitioners must balance the cost of testing concepts and the potential profits it will reap [23,24]. The failure to do so has led some organizations to avoid it in total due to the uncertain return on investment [2]. Since resource considerations, time and costs are the primary barriers to its application in industry, understanding how to prototype economically can not only help companies leverage prototyping to save cost but also increase efficacy [1,2].

It is the goal of this work to study the economies of prototyping as part of the design process, with the intention of developing targeted strategies and heuristics to assist designers, practitioners, and researchers to prototype effectively and economically.

Research Questions

In this research, we explore an important aspect of prototyping for practicing designers and engineers—its economies. For clarity, we will define some important terms. The use of the group of words "economies," "economic," and "economical" in the context of prototyping is in accordance with what Oxford Dictionary defines as giving good value or return in relation to the money, time, or effort expended [25].

Prototypes are used to gain design information that will allow a team to advance "in product [systems] development with minimal expenditure of time and cost" [1]. "There may well be a trade-off between the design information gained and the resources expended to gain that information," and we seek to understand this trade-off more deeply [5].

Our research adopts a few key elements from existing work that study the roles of prototypes in companies and their impact on innovation [3,21]. First, we examine projects that "create physical end products, which have been studied less than digital products" [3]. Second, we study prototyping in industry projects rather than academic experiments, as there is not a solid understanding of how prototyping facilitates success even though they are considered critical to the success of companies [3]. Third, we observe how design teams execute the project in their natural work environment instead of a controlled experiment. This inductive approach captures the full spectrum of complexity that practitioners face and allows insights relating to industry projects to emerge organically [26]. Finally, we extend our study to service, and system design contexts, to understand how generalizable our models are.

The goal of our work is to be able to understand the economies of prototyping and the corresponding dimensionality—more concretely, how fidelity (estimated by time, cost, and effort) may affect value (design information gained), or not—through empirical study in the natural work environment where expert design teams prototype for industry projects.

Combining our motivations with the work by leading researchers in this field, the driving research question we seek to answer is: *What is the tradeoff between design information gained and the resources expended in prototyping to gain that information?* We expect that more resources expended in prototyping will tend not only to yield more information, but also anticipate exceptions that will carry insights into prototyping economically.

Other supporting questions we would like to answer include: *How does the fidelity of prototypes affect their value? How do we quantify the value of prototypes? What strategies can we*

Fig. 1 Physical prototypes made by SUTD-MIT International Design Center exploring concepts for a new payment device for children

implement to be more economical and cost-efficient in prototyping? Can the observed patterns regarding prototyping efforts generalize across varied design contexts?

Research Methodology

Figure 2 illustrates the research methodology undertaken here. The research follows three projects. By studying the execution of an industry project involving the development of a FinTech B2C (Financial Technology business-to-consumer) product, the research problem will be refined to one that is both academically and practically worthwhile and realistic as data are recorded for analysis [27]. In these projects, a team of designers developed prototypes and presented them to clients. Clients then reported needs and insights in response to these prototypes. The time spent in development of each prototype was also recorded. This constitutes the first phase of the research.

In the second phase, these insights were mapped to the actual list of final design features. This allows for a measurement of the features or needs identified to be mapped to a specific prototype. This information is correlated to time expended in fabrication of each prototype. In order to evaluate principles for economic prototypes, a residual analysis of the marginal return on investment of each prototype was performed. Characteristics of highly valuable prototypes were extracted and formulated into principles through iterative evaluation by the researchers with inter-rater testing; this is done using an open-ended approach [28]. Finally, the same analysis, once defined, is extended to a system and a service design case studies as a preliminary test for cross-domain applicability. This particular approach can be defined as a descriptive case study analysis with multiple cases [29], in which quantitative measures are also taken to supplement qualitative insights.

Industry Projects

For this research, we study the prototyping efforts of three industry projects. These projects were selected as they covered breadth in the types and scales of design efforts, and also involved substantial prototyping. A case study on a FinTech B2C product will first be used to establish our method of analysis. In the second half of the paper, we will introduce and analyze two supporting projects with the aim of extending our findings to systems and service design.

It is noteworthy that these industry projects were executed as a participatory design project in which two out of the eight co-authors were also engineers or designers in the project. By setting it up as an inductive study, we ensured that the results of the project were neither influenced by the research objectives nor was the objectivity of the research compromised. Data from the design project were objectively recorded as is and any subjective decisions or constructs used in the research were tested for inter-rater reliability to ensure objectivity. Hypotheses were formulated and tested only after the design projects were complete.
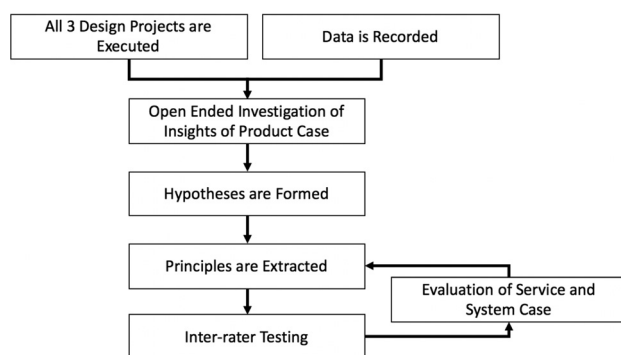

Fig. 2 Research methodology

Driving Case Study: FinTech B2C Product. As part of Singapore's "Smart Nation" agenda to become a cashless society, a leading local bank tasked the design company with creating an innovative product service that will help move the younger generation onto digital payment [30]. The design company—which has been established for eight years and employs more than 200 people—assembled a design team of four consisting of a product manager, mechanical engineer, electrical engineer, and industrial designer to work on this design project. The team iteratively diverged and converged on ideas, producing more than 200 prototypes in three stage-gated development phases over the course of 6 months. Eventually, the team narrowed down to a best-fit design concept that was designed for manufacturing and acclaimed by both the client and users.

To ensure consistency in our analysis, we only study the first phase of the entire design process—marked out by the red box in Fig. 3—where the objective, resources, and timeline are homogenous across all prototyping efforts. In this phase, the team explored and diverged to gather information by generating a range of new concepts [1]. Prototyping efforts for exactly 50 unique design concepts were executed in parallel to more cost-efficiently discover unseen constraints and opportunities, enumerate more diverse solutions, and obtain authentic and diverse feedback [31,32].

Subsequently, a 3-h long design review—where the clients interacted with the prototypes—was organized so that the team could effectively convey the concepts [8] and obtain answers to specific design questions [4]. Since the clients were not fully aware of their needs [33], this method was particularly useful in uncovering latent needs [34], understanding underlying principles [35], as well as sharpening categorical boundaries [36].

At this juncture, to avoid confusion, we will define some terminologies that will be used throughout the paper. A "prototyping effort," according to Moe et al., is defined as the creation of prototypes and testing for a single design concept [12]. Contrastingly, a "prototype" refers to a single instance of representation of the design concept. Accordingly, each prototyping effort may consist of one or more prototype iterations of varying fidelity that were created using different methods to test a single design concept [37].

Data Collection

The project data that were collected for research purposes came from a multitude of sources: feedback from users during testing and interviews, assessments from clients during review sessions, design team's internal records of the prototyping process, and a retrospective review of the prototyping journey. The complete set of data recorded is described in Table 1.

The idea was to let the prototyping process in the B2C product project unfold organically under the plans of the design team without any influence or input from the research team. The research team would, however, be close by to observe, interview, and record the every relevant empirical data of the prototyping process at every stage. This way, the data that were collected would arguably capture a complete and unadulterated picture of the prototyping process. From this set of data, we build our models.

Once the analysis had been defined and tested using the B2C product project for core analysis, the same methods of data collection and analysis were applied to the system and service design projects. Specifically, the same quantitative and qualitative data were captured.

Economic Analysis Approach: Cost Versus Value

Recalling that the goal is to understand the economies of prototyping as part of the design process, we begin by defining what prototyping economies mean in the context of this study.

The economies of prototyping capture how designers choose the "least expensive" ways to prototype that are still effective, using fast and inexpensive methods to build prototypes that are
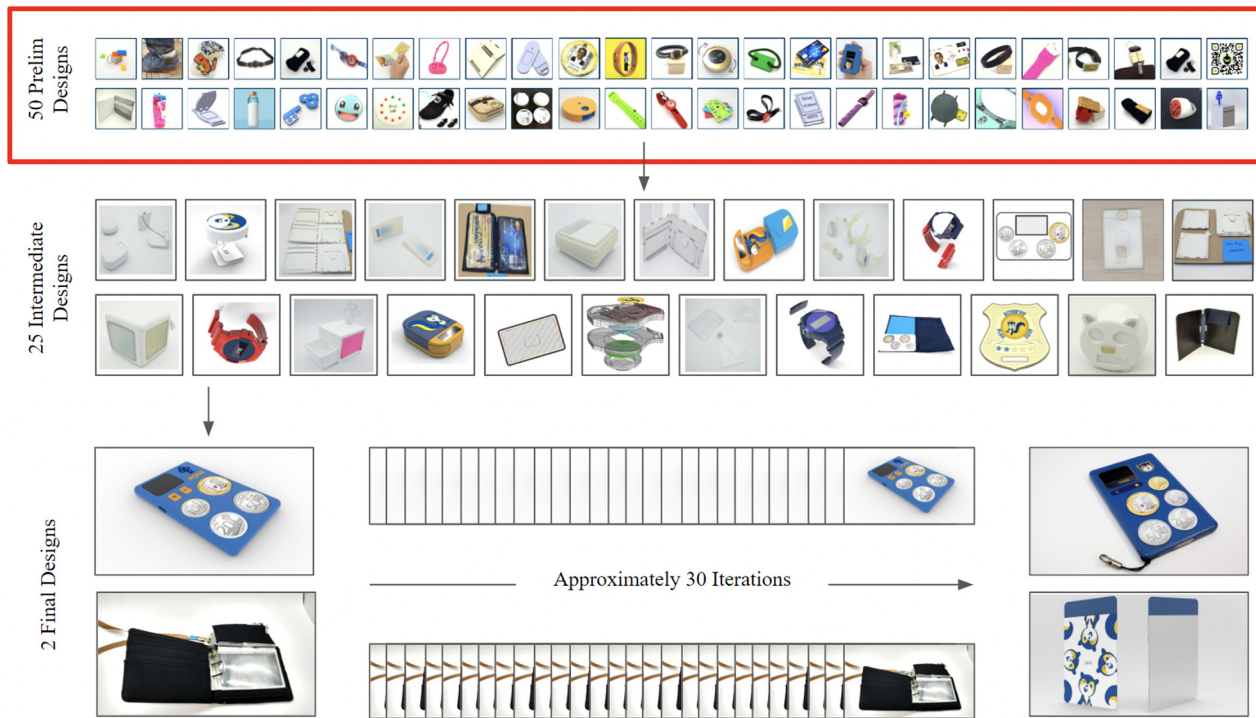
Fig. 3 Overview of design concepts prototyped across all phases of the FinTech B2C product project

sufficient to provide the required information [38]. Thus, we propose for this study that the input be effort, or time expended (as a proxy for fidelity) [4] and the output be value. In the sections How to Quantify Fidelity and Value of Prototyping and Design Information, we will define more concretely what fidelity and value mean in the context of our case study, but at this junction, it is important to note that understanding the relationship between investment on prototyping and design success [4,39,40] is critical for a practitioner to make decisions [1].

We set the stage for understanding fidelity and value by clarifying that the goal of using prototypes in the FinTech B2C project was to more deeply understand the clients' needs for the form factor of the payment device and its "implementation" [41].

How to Quantify Fidelity?. Researchers have suggested other ways of measuring fidelity. For example, by comparing it with respect to the final model [42], or by using different dimensions of a prototype such as visual realism, interactivity, depth of functions, and breadth of functions [6,43–47]. An example of one such dimension is illustrated in Fig. 4 where a functional model was created to determine the breadth of functions for a single prototype. However, these ways of quantifying fidelity have their subjectivities as they are influenced by the specific design context [5] and the stage of development [4].

Therefore, we explore an alternative way of measuring fidelity—one that is more quantifiable and less subjective. On the premise that the building of prototypes is a trade-off between

Table 1 Types of data recorded from prototyping process

	Example
Quantitative data	
Number of prototype iterations for each prototyping effort	4
Cost of making each prototype iteration (S$)	$40
Time spent for each prototyping effort (hours)	5
Qualitative data	
Description of design concept for each prototyping effort	Payment chip integrated with a popular toy.
Hypothesis for each prototyping effort	Clients would desire a form factor that appeals to children as a toy.
Photo and renders of prototypes and render	
Methods of prototyping	CAD, 3D Printing, hand assembled
Objective of the prototyping effort	Communicate and explore
Design information gained for each prototyping effort	Should not be playful or distracting.
Preceded by which ideas	Keychain, Toy
Succeeded by which design concept	None

fidelity and the time, effort, and cost required to produce that prototype [4], we propose that resources, such as time, cost and effort, expended can be a justifiable estimator for fidelity by proxy. This is a known correlation in the simulation literature between time spent and model fidelity, and the corresponding literature ultimately recommends at a high level similar strategies as uncovered in this work, multiple low fidelity samples and care in executing high fidelity models, albeit the domain of execution differs [48–51].

It is worthy to note that time, cost, and effort expended in prototyping are arguably correlated and often proportionate—greater effort consumes greater time and increases person-costs. In the concrete case of the B2C product project, the cost and time expended for each prototyping effort are highly correlated with a Pearson's correlation coefficient of 0.743. To avoid the problem of multicollinearity and unobvious dependencies among these factors, we will choose only one out of three.

In this case, we choose to use time expended as a proxy for fidelity because as it directly translates to the realization of a prototype given a fixed team size, expertise, and access to resources. This is sufficient and more suitable than cost, which is primarily driven by the choice of prototyping method and may change by
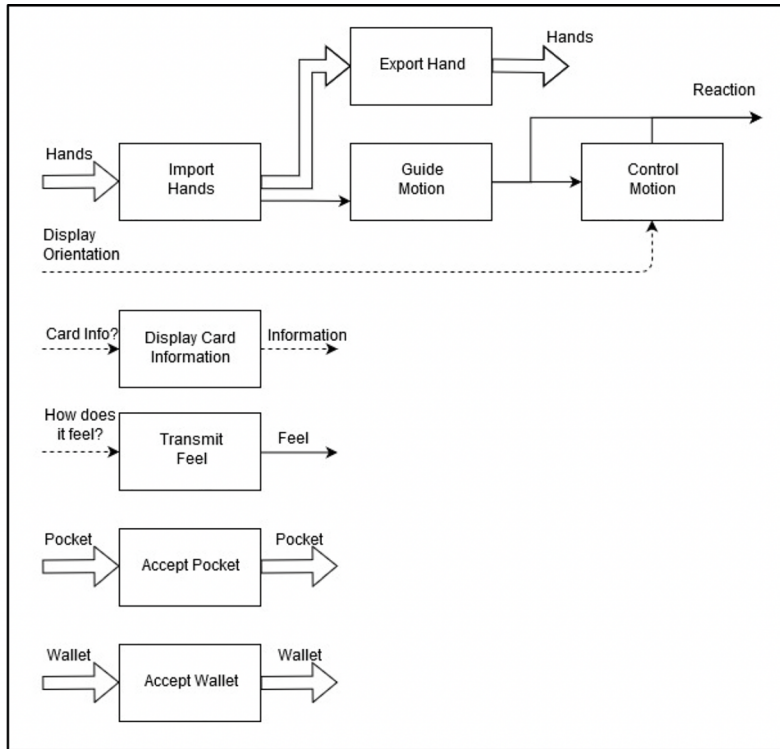

Fig. 4 Functional model (top) of "card pack swivel" prototype (bottom) reveals a breadth of eight unique functions

context [20]. The approach to estimate cost via person-hours has been demonstrated as a means for normative economic analysis in design since the 1980s [52]. For our study, we define the time spent for each prototyping effort as the number of hours that is expended in translating each of 50 unique design concepts from a sketch into a prototype that is capable of interaction with the clients, users, and stakeholders.

Value of Prototyping and Design Information. In quantifying the value of prototyping, we first establish that in the development of a product-service-system, "need" information necessary to derive insights or intuitive foresight resides with the customers, users, and stakeholders [33]. On this premise, the value of prototyping in the industry project lies in uncovering such "need" information that moves the development team forward [1]. Accordingly, design information gained from each prototyping effort becomes the obvious metric that represents value and will be selected as output for our analysis.

For the case of the driving B2C product project, design information was derived from a process of engaging the clients in a 3-h long design review session where 50 design concepts were presented to them using prototypes. The prototypes elicited important feedback and needs from the clients. The information gathered were subsequently clustered into 19 unique pieces of design information based on their affinity and recurrence. Overall, a total of 19 pieces of design information, listed in Table 2, were gained from the 50 prototyping efforts.

To transform this textual design information into quantitative data that we can plot against time, we developed a way to quantify a value for every design information. A rubric to measure the value of design information was developed and tested for inter-rater reliability with four expert raters using the Fleiss' kappa method. It was iterated on through convergent coding until the kappa value was 0.83 and we were confident of using it in the analysis. All 19 pieces of design information were then rated on a scale of 1–4 according to the rubric described in Table 3. The corresponding value scores for each piece of design information can be seen in the right-hand column of Table 2.

For examples, the "need to simulate counting money" was rated to have a value of 4 as it revealed a disruptive opportunity for the design problem, while the design information that merely reinforced the need for the product to be "cost-efficient for large volumes" was rated with a score of 1.

Some prototyping efforts elicited more than one piece of design information while others yielded none. Hence, to calculate the aggregate value captured by each prototyping effort, we summed up the value score of all the design information they elicited or created.

We observed that the "minimalist" design—shown in Fig. 5—revealed only one piece of information about the clients' latent need for a practical design aimed at an older demographic of their target users. As this design information was rated as incremental, the total score of this prototyping effort was two (2). On the other hand, the "LED vending token" design elicited three pieces of information: the disruptive latent need to simulate counting money in the device, an incremental latent need to have the design compliant with all payment infrastructure island-wide, as well as deepening the key need to avoid complex implementation due to the diversity of stakeholders involved. This design information was rated four (4), two (2), and three (3), respectively, giving the prototyping effort an aggregated score of nine (9).

The aggregated scores of all prototyping efforts were normalized using the minimum and maximum aggregated value score of 0 and 9, respectively. For example, the "minimalist" and "LED vending token" prototyping efforts ended up with normalized value scores of 0.22 and 1, respectively.

Experimental Data

A total of 50 distinct prototyping efforts were executed in this phase, providing us with 50 data points to analyze. Each prototyping effort was executed for a single design concept. While more than 50 prototypes were created due to exploration and refinement of the design ideas (iteration on a single concept), only 50 prototypes representing each design concept were presented to the clients [15]. It is important to note that the 50 prototyping efforts were recorded in the same stage of the design process—they were built for the same goal of understanding the clients' needs and underwent the same review process. By constraining our analysis as such, we necessarily establish consistency across all our data points.

Quantitative Analysis. A descriptive statistics of the 50 data points containing two variables that we will use for quantitative analysis is seen in Table 4.

To analyze our data, we created a scatter plot of "normalized value" against "normalized fidelity" using the 50 data points, as shown in Fig. 6. In this case, a Pearson's data for both axes is normalized on a zero to one scale using the feature scaling method described by the following equation:

$$X_{\text{normalized}} = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

where the minimum and maximum are taken across the data set for a single variable.

We observed that the distribution has a mean normalized value of 0.391. Since the data follow a Gaussian distribution, we are able to find the Pearson correlation coefficient of 0.530, which indicates a strong correlation or high degree of association [53].

Next, we tested fitting linear, polynomial, and logarithmic regression models to the data. As observed in Table 5, fitting a second-order polynomial curve yielded the highest r-squared value of 0.284. However, the intercept and coefficients of the second-order polynomial curve are not statistically significant, yielding p-values of 0.195, 0.082, and 0.6296.

Table 2 Design information and score

Need information	Rated value score
Need to simulate counting money (financial literacy)	4
Need to be practical	2
Need to avoid complex implementation	3
Need to build on existing payment behaviour	3
Need to be universally compliant	2
Need to have personalization	3
Need to be cost-efficient for large volumes	1
Need to maintain or decrease transaction time	1
Need to be secured (not a loose item)	1
Need to be serious (not be playful/ distracting)	2
Need to command security/ importance	2
Need to be durable	1
Need to have innovative element	2
Need to track expenditure (financial literacy)	1
Need to encourage savings (financial literacy)	2
Need to have clear use case	2
Need to adhere to payment infrastructure	4
Need to allow recognition of money (financial literacy)	4
Need to leverage use of student card	4

Table 3 Rubric to rate value of design information

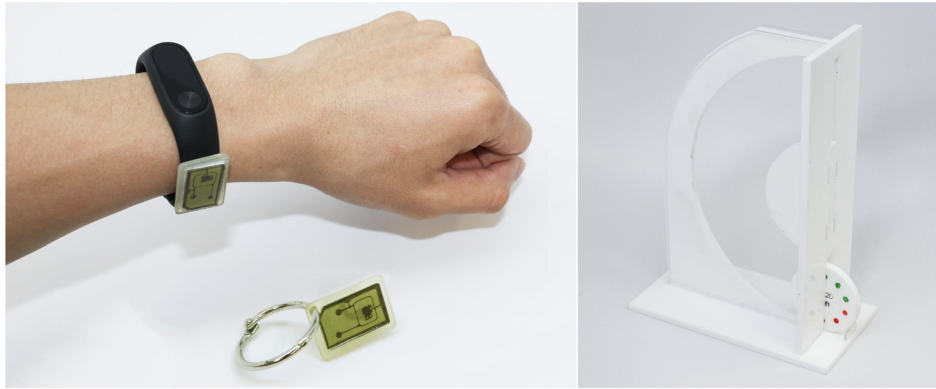| Value score	Impact of design information
1	Confirms a known need.
2	Reveals an incremental need.
3	Deepens understanding of a key need.
4	Reveals a disruptive latent need.

Fig. 5 'Minimalist' (left) elicited one piece of design information for an aggregate score of two (2) while the 'LED vending token' (right) elicited three pieces of design information for an aggregate score of nine (9)

Table 4 Descriptive statistics of the dataset

Non-normalized variable	Mean	Median	Standard deviation	Min	Max
Fidelity (hours)	3.24	3	1.825	1	9
Value	3.52	4	2.169	0	9

Table 5 r^2-values for various trend-line fits

Trend-line fit	linear	poly-2	log
B2C product	0.281	0.284	0.265

On the other hand, fitting a linear regression model to the data, seen in Fig. 6, produced comparatively better results with an r-squared value of 0.265. More importantly, its intercept and coefficients are statistically significant with p-values of 0.0086 and $7.55 \times 10^{-0.5}$, respectively. The linear regression line describing the relationship between the dependent and independent variables in the following equation:

$$\text{Value}_{\text{normalized}} = 0.164 + 0.630 \times \text{Fidelity}_{\text{normalized}} \qquad (2)$$

It is important to note that the low r-squared value observed in Table 5 stems from the nature of how the design information was obtained; the subjectivity of human factors such as interaction and psychology causes less of the variance to be explained by the model. Nonetheless, this is acceptable because we are using the model to understand relationships and outliers rather than for predictions.

To identify the outliers in the model, we first calculate the standard deviation of its residual, which is 0.204. From this result, we can identify which data points have residuals of more than twice the standard deviation of the residuals. Accordingly, two outliers at (1, 0.77) and (0.54, 1) were identified with residual 0.544 and 0.486, respectively. We will later study these outliers in more detail as part of our analysis.

At this juncture, we allude to the perspective that the use of this fitted curve is to give us a basis to compare with theory; its spread and statistical characteristics are not the most important parts of our analysis. Rather, the most critical aspect is what the distribution of the data points tells us. The general trend and the outliers all reveal important insights, which we will discuss in greater detail in the Impact Versus Time and Analysis of Prototyping Economies: FINTECH B2C Product sections.

Qualitative Analysis—General Trend. Given the spread of our empirical data points, we postulate that we can derive deeper
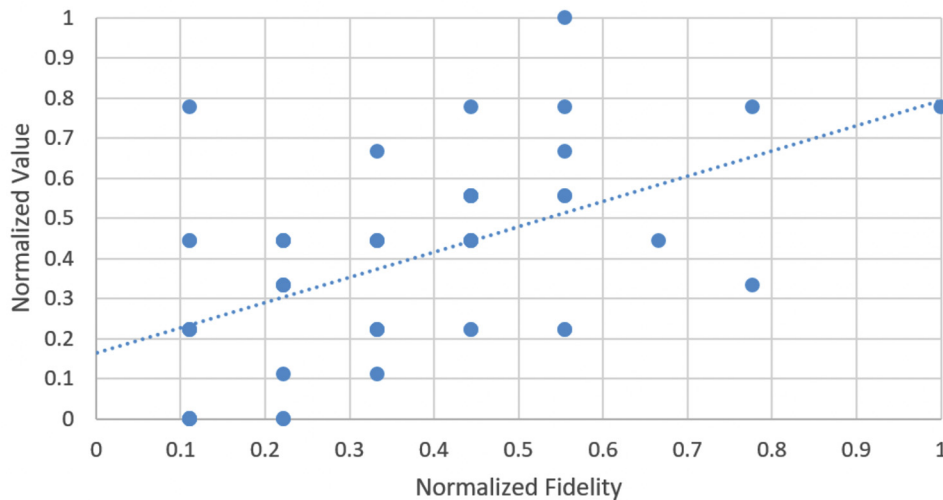

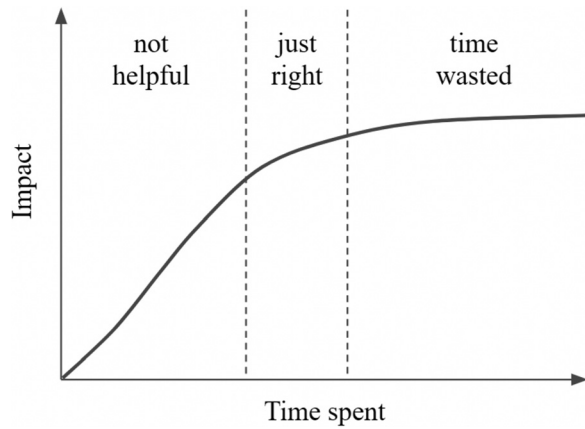**Fig. 6 Normalized value versus normalized fidelity**

Fig. 7 McElroy suggests that there is a balance between time spent and the value gained [6]

meaning through understanding these plots spatially. How can we categorize the value–fidelity relationship meaningfully? At first glance, it is difficult to identify a pattern in the data spread. However, the high degree of Pearson's Correlation Coefficient tells us that there is a strong correlation between the fidelity and value [53]. We also observe a prevailing void in the bottom right and top left corners of the plot—indicating that very few prototyping efforts were of high fidelity and low value or low fidelity and high value. To better appreciate the implications of this distribution, we will carry out two analyses: explore McElroy's work on prototyping impact versus time, as well as study and categorize outliers in the scatter plot.

Impact Versus Time. McElroy's "prototyping for designers" postulates that there is "a balance between the time and effort it takes to make a prototype and the value you'll get from testing at that specific fidelity" [6]. It illustrates the three phases of that relationship as shown in Fig. 7. McElroy believes that there is a right amount of time and effort that should be expended to achieve the optimal impact of prototyping; anything less would be not helpful and anything more, a waste of resources [6].

McElroy's work provides us with more perspective for understanding the relationship between value and fidelity. In early data exploration phase, we observe a qualitative trend in our data distribution that

is not too far from McElroy's proposal. Impact increases with time spent (proxy of fidelity) and the asymptote on the right-hand side suggest a limit to the amount of value high-fidelity prototypes can yield even with its added dimensions. On the other hand, McElroy's conjecture that there exist three distinct categories of impact for prototyping depending on the time spent deviates from what we observed. From our results, we could not categorize all low fidelity prototypes as unhelpful nor can we agree that high fidelity prototypes are always wasteful as we will find and discuss in the Analysis of Prototyping Economies: FINTECH B2C 499 Product section. If this way of categorization is not suitable for the spread of our empirical data points and what we observed of the prototypes, how then can we better categorize the value–fidelity relationship?

Outliers and Categorizing Prototypes. We propose categorizing the prototypes using the standard deviation of the residuals. We previously identified two outliers two standard deviations away from the regression line at (1, 0.77) and (0.54, 1) with residual 0.5435 and 0.4857, respectively. We take that idea further by segmenting the plot into five distinct spaces using standard deviation as shown in Fig. 8.

These spatial segmentations give us a new perspective to study the outliers and various groups of prototyping efforts. From the green regions, we can abstract good practices that will allow designers to create highly economical prototypes. While in the red region, by studying prototyping efforts that did not reap value as expected, we aim to derive strategies to avoid such pitfalls.

Deriving Insights

With the data points all categorized based on standard deviation from the regression line, we can isolate the prototyping efforts within each category and study their characteristics, such as fabrication method, purpose, and dimensionalities. The idea is to identify patterns and commonalities among these prototyping efforts that would explain the value they generated and extract prototyping heuristics that practitioners can exploit. Table 6 below describes basic prototyping profile of each category.

Analysis of Prototyping Economies: FINTECH B2C Product

Dark Green Region: Exceptionally Economical Outliers. The two prototyping efforts in this outlier category are "card pack
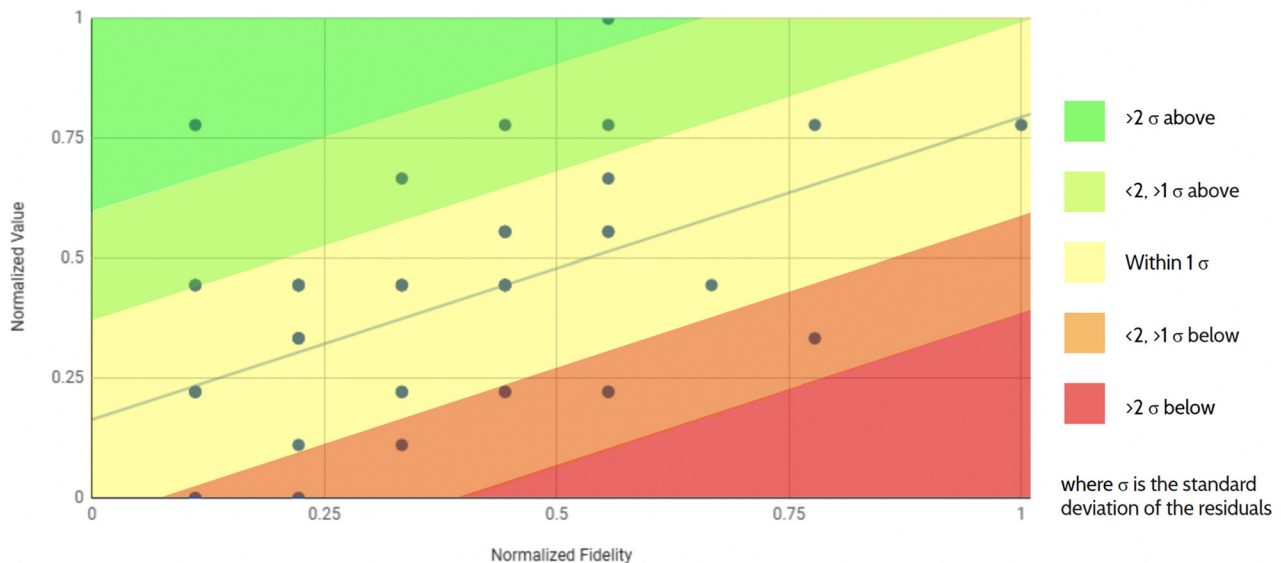

Fig. 8 Segmenting prototyping efforts into five categories using standard deviation of residual for B2C product project

Table 6 Categorizing the prototyping efforts for analysis

Category	Color code	Observation	Number of prototyping efforts
> 2 σ above	Dark green	Low fidelity, high value	2
<2, >1 σ above	Light green	Low fidelity, low value	1
		High fidelity, high value	3
Within 1 σ	Yellow	Directly proportional	35
<2, >1 σ below	Orange	High fidelity, low value	3
		Minimal interest from clients	6
> 2 σ below	Red	—	0

Fig. 9 Two low fidelity prototyping efforts that achieved high value score by effectively using simple tools and craft
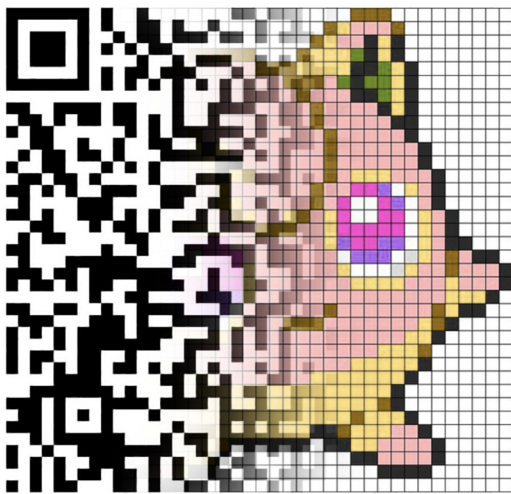
Fig. 10 "Cartoon QR code" was a low fidelity prototype that tested core concept of a different payment mechanism

swivel" and "LED vending token," which were observed to have low fidelity but generated exceptionally high value; shown in Fig. 9. The exceptionally high value was a combination of two factors—a substantially differentiated design concept was tested and the prototypes were made with high-cost efficiency. By analyzing the method by these prototypes were made, we observed that the design team employed simple tools and basic craft like cardboard, markers, gluing and cutting that reduced the cost, time, and effort for prototyping substantially.

Light Green Region: Highly Economical Prototypes. The prototypes in this region can be further differentiated into two subcategories—the prototypes with lower fidelity, that required less effort to product, and were of low value, and those with high fidelity, that required high effort to produce, and were of high value. For both subcategories, we will study the purpose of the prototyping for "cartoon QR code," "super sticker," "slap band slider" and "hybrid wallet."

For "cartoon QR code"—shown in Fig. 10, the team employed an extremely low-cost prototype to test the core concept of using a completely different form of payment. This prototyping effort revealed a unique piece of design information that, although was of low value, would have otherwise not been discovered—the design team was constrained by the existing payment infrastructure of accepting only contactless payments; as such, QR code payments, which required the use of cameras, were not supported.

The prototypes in the other subcategory were observed to be high fidelity, high effort to product, and generated high value. When we analyzed the purpose of these prototypes, we learned that they were all substantially differentiated from the other prototyping efforts. As shown in Fig. 11, "super sticker," "slap band slider," and "hybrid wallet" were purposefully made to test the differentiated concepts reusable adhesive gel, counting money, and modified wallet.

Yellow Region: Directly Proportional Economies. A total of 35 prototypes were found within one standard deviation of the model's residuals. Since there are numerous prototypes in this category, there were many aspects we could investigate in depth. In particular, from the study of the prototypes dimensionalities [6] and method of fabrication, we were able to derive insightful patterns.

We observed that prototypes in this category that generated higher values had greater dimensionalities. For example, the "adaptable token 2" was not only visually representative of the concept; it contained a breadth of well-developed features that allowed users to interact with it, such as the retractable cord and the clip. The higher dimensionality contributed to a normalized aggregate value score of 0.78. Conversely, other prototypes that generated lower value typically had lower dimensionality. "Card wristband," "Dual-function token," and "3 M dual Velcro" were all not visually representative of the concept and only had one
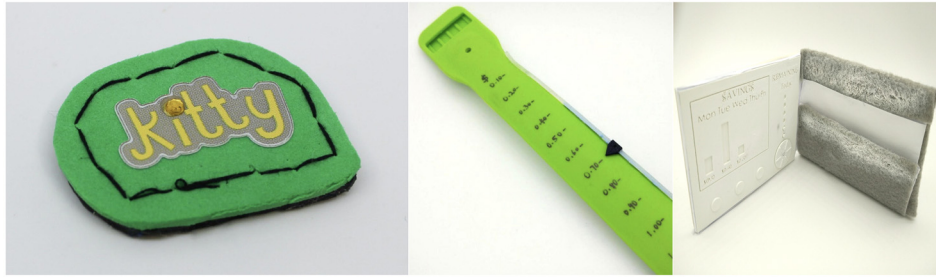
Fig. 11   From left to right: "super sticker," "slap band slider," and "Hybrid wallet" are high fidelity prototypes that were substantially differentiated to gain unique design information

Fig. 12   Higher dimensionality "adaptable token 2" (on the left) attained a value score of 0.78 compared to lower dimensionality prototypes like "card wristband," "dual-function token," and "3M dual velcro" (three from the right) which scored 0.33, 0.22, and 0.33, respectively

interactive function for the clients to test. Comparison of prototypes is shown in Fig. 12.

By studying the method of prototyping, we identified one prototyping effort that increased its value by augmenting the physical prototyping with digital representation. As illustrated in Fig. 13, "smart student card" demonstrated the interactivity of this design concept using a physical prototype but brought to life the idea with a rendered image that was visually representative. By augmenting the physical prototype with a visually accurate render, the team was able to elicit design information about personalization of the product, which would not have been possible with the physical prototype alone.

Orange Region: Lower Economical Prototypes. Similar to the above, the prototyping efforts in this category can be further

divided into two subcategories: the high fidelity (high cost), low-value ones, and the ones that helped the team identify design directions that are not worth pursuing due to minimal interest from the clients.

By studying the purposes of the three prototyping efforts that had high fidelity but generated low value, we learned that they generated low value because resources were invested in prototyping smaller details when bigger ideas were still untested. As a result, these prototyping efforts did not yield the value where resources were invested. As shown in Fig. 14, "rotating bezel coin," "fidget spinner" and "adaptable token 1" were created with high visual representation and multiple interactive features such as rotatable components. However, the fundamental ideas of having a loose item or a toy-like payment device were rejected from the onset, negating further evaluation of its more microfeatures.

Fig. 13   A single design concept was realized as a physical prototype (right)— to demonstrate its interactivity—and also as a rendered image (left) to illustrate it visual elements; each eliciting different design information
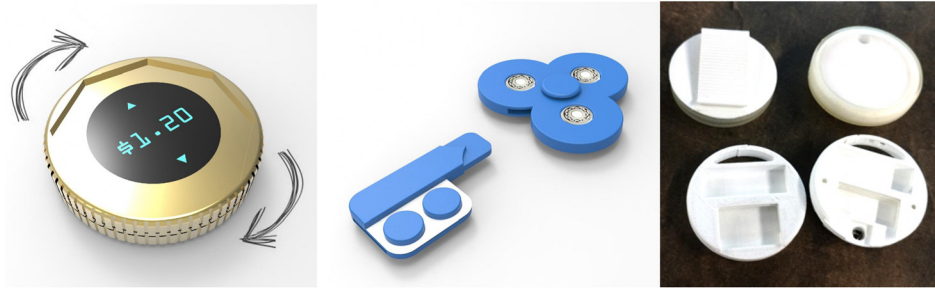
Fig. 14 From left, "rotating bezel coin," "Fidget spinner," and "adaptable token 1" were all high fidelity prototypes with many small details that ended up being wasteful because its larger idea had not been tested first

Table 7 Overview of case projects

	B2C product	System development	Service design
Industry	FinTech	SpaceTech	Healtd
Project nature	B2C payments product	Aerospace system development	Healtd service design
Duration	6 months	24 months	3 months
Team Size	4 people	4 people	16 people
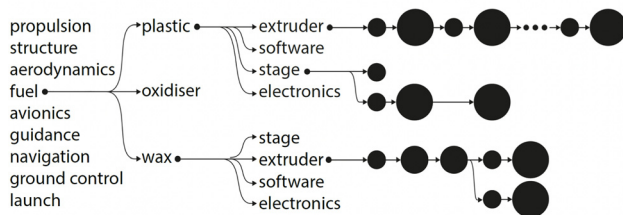
Fig. 15 Full scale test of the commercial grade engine[1] using 3D printed components (top); system segmentation and associated prototyping strategy, dots indicate sequence, large dots are higher fidelity (bottom). Courtesy gilmour space technologies.

Extension to With System and Service Cases

Having defined a method for categorizing and analyzing a product-driven project to derive insights that can help practitioners, we seek to understand how this approach of analysis can be generalized by extending it to system and service realms so that we can create a more holistic understanding of prototyping [3]. We will analyze and evaluate—in the same methodological fashion—two other industry projects that similarly employed prototyping heavily in the design process. An overview of the system and service projects with respect to the driving product project is described in Table 7.

System Case Study: Additive Manufacturing for Aerospace. The objective of this project was to create a novel additive manufacturing process for use in hybrid rocket propulsion [54] by

the client, a space start-up company. To tackle this complex system, the design team deconstructed the project into critical subsystems—as seen in Fig. 15—and ran 80 unique prototyping efforts over two years to explore the design space, refine concepts, and evaluate subsystem interactions. The project eventually resulted in the successful engine test of an orbital class rocket engine.

Service Case Study: Service Centers. In an effort to improve service experience, staff satisfaction, and operations efficiency, 22 health service centers in Singapore were redesigned by the design innovation team at SUTD-MIT IDC. Over a span of three months, the team engaged in 54 prototyping efforts of varying fidelity to explore and evaluate ideas on operating procedures, data management systems, and interior architecture. Some resulted in single device interfaces, while others manifested as a large-scale simulation exercise of the integrated center. Exemplar prototypes are seen in Fig. 16.

Repeated Analysis on System and Service Projects. To analyze the system and service projects, we applied the same approach of input–output quantification to the 80 systems and 54 service prototyping efforts and then fitted them to a linear regression. The resulting scatter plot and regression lines are seen in Fig. 17, together with the product project presented in Fig. 6 to serve as a reference.

Key insights that we gathered from studying this collection of plots are listed below. This fundamentally links to the original research questions on the relationship of fidelity (time expense as proxy) and value:

(1) The systems and service projects reaped increasing value from prototypes with higher fidelity. This correlates with our findings from the product project.
(2) Less for a few outliers (before residual analysis), bottom right and top left corners are generally sparse—indicating avoidance of high fidelity prototypes that generate low value and difficulty in creating low fidelity prototypes that generate high value, respectively.
(3) A concentration of points in the lower left region indicates that a large portion of prototypes is created at low fidelity; in line with being economical. On the other hand, only a small portion of all prototypes created was actually of very high value;

Fig. 16 Example prototypes for service project; leftmost—earliest prototypes; rightmost corner—live simulations

(4) There exist a number of outliers—especially for the systems project—which represents exceptions in our prototyping practices that we can extract valuable heuristics from.
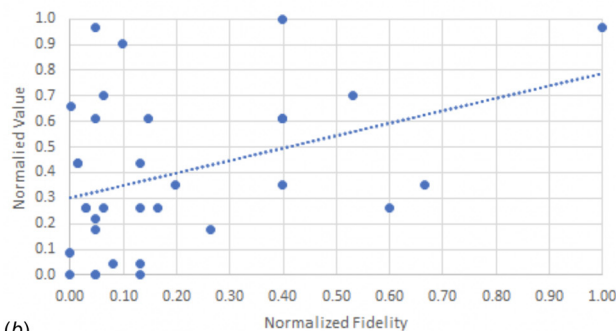
To analyze the prototyping economies in both projects, we categorize the data points (prototyping efforts) into the five color-coded economic regions as previously defined in Table 6. In each category, we will study the trends thoroughly for additional insights we can abstract.
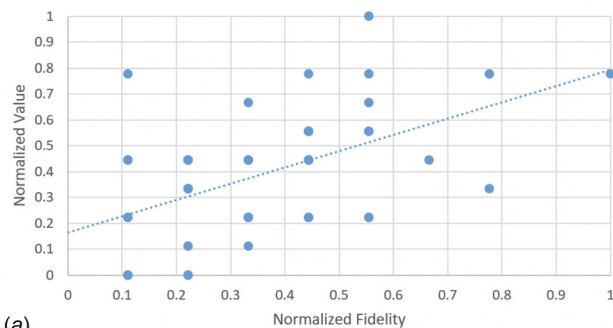
(a)

(b)
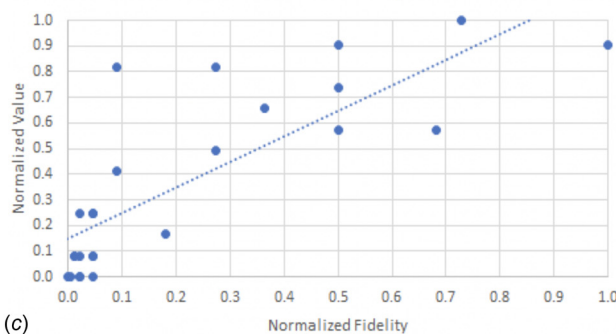
(c)

Fig. 17 Normalized value versus fidelity (a) product, (b) system, and (c) service

Analysis of Prototyping Economies: System Development

Prototype efforts that turned out to be exceptionally economical in the systems project typically involved benchmarking or testing of existing designs. Their value lies in drawing upon the vast repositories of past projects and focus on "finding the wheel" so to speak, rather than re-inventing it. For example, benchmarking and conducting basic tests on the material property—shown in Fig. 18—identified a large number of unexpected latent needs, such as the viscosity of the mixture, that turned out to be critical to the project, and would have otherwise not been predicted by standard models of composite viscosity as it did not account for certain critical interactions in the mixture.

On the other hand, prototyping efforts that were not so economical were characterized by underperforming subsystems, such as the first integrated printer subsystem prototype and the extruder head design seen in Figs. 18(b) and 18(c). In each of these subsystems, dozens of iterations were created with marginal benefit in performance and target quality was never achieved. The reason being that deep functional flaws were already prevalent before the iterations, yet evolutionary prototyping was still conducted. In a complex system, these fundamental problems should have been addressed upstream, and if necessary, re-abstract and start afresh with a new approach rather than only facing it when the subsystems are being integrated.

Analysis of Prototyping Economy: Service Design

The highly economical prototyping effort in the service project turned out to be that involving low-cost simulation of activities and real data, as illustrated in Fig. 19. For example, the simulation of patient foot traffic revealed a variety of latent user needs regarding patient flow that neither prior observations nor static concepts of layout had captured. Another simulation concerning user experience revealed key patient–staff interaction and patient information tracking that was of immense value to the improvement of operations management in the service centers. Collectively, the most valuable prototyping insight gained was to employ simulation even for low fidelity concepts and base it upon on real data.

Even among the moderately economical prototyping efforts simulation was an important tool; the only difference was that they were of higher fidelity due to increased requirement. For example, to test the concept of providing patients with a map of the service center, the team had to make a site visit and larger number of personnel was involved.

Prototyping Principles

Based on the findings from our data and analysis in the sections Analysis of Prototyping Economies: FINTECH B2C Product and Extension to With System and Service Cases, we can abstract and express the results as a set of heuristics for economical prototyping so that practitioners can exploit them. These design principles/heuristics are created according to the methodology and format provided by Fu et al.: "*A fundamental rule or law, derived inductively from*
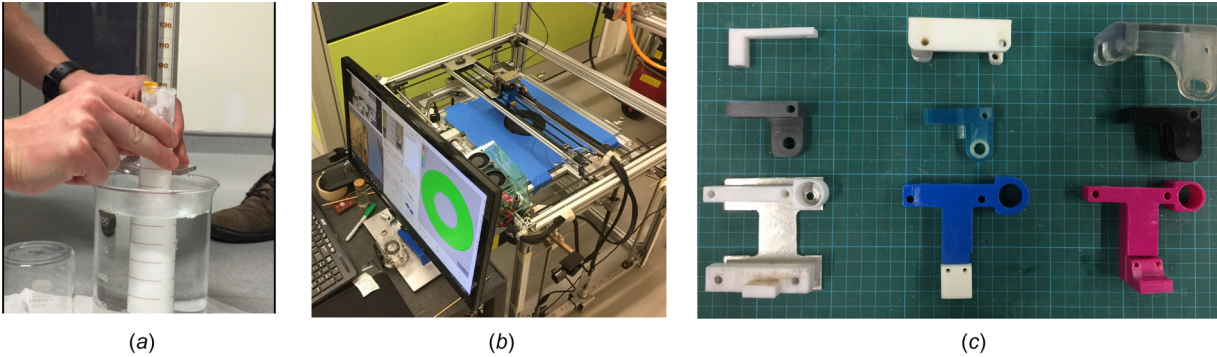
Fig. 18 Prototypes; system samples: (*a*) Examples with residual two standard deviations or more above the norm: material property tests, (*b*) Examples with residual within one standard deviation of the norm: first integrated printer subsystem prototype, (*c*) Examples with residual between one and two sigma below the norm: iterations on extruder head design
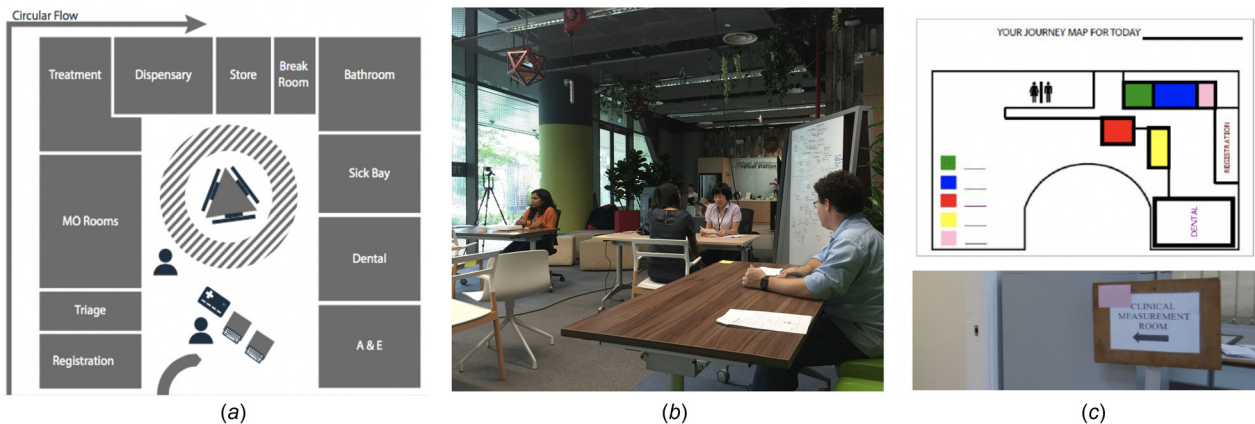

Fig. 19 Prototypes; service samples: (*a*) Examples with residual two standard deviations or more above the norm: simulation of patient flow pathways, (*b*) Examples with residual more than one but less than two standard deviations above the norm: actor-scenario based simulation of patient traffic flow, (*c*) Examples with residual within one standard deviation of the norm: map to identify patient flows in situ experiment

extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution [55]." The process of how we derived these heuristics from our empirical data and analysis is illustrated in Fig. 20.

Heuristics From B2C Product Analysis

Aim for Increased Dimensionality. To prototype economically, our study suggests aiming for increased prototype dimensionality as more resources are expended. The increase in breadth and depth of functionality, interaction, and visual resolution will improve the chances of revealing unique and deeper design information [6]. Furthermore, prioritizing which dimension is important for a specific prototype will help designers focus and save time and effort [6].

Test Core Concepts With Low Fidelity Prototypes. Low fidelity prototypes that are easy, fast, and inexpensive to make [6] are not necessarily unhelpful. Conversely, they may be strategically critical, especially in the early stages of development where the relaxation of prototyping requirements does not have an adverse effect on final performance [1]. Low fidelity prototyping enables quick exploration of an unknown space of designs to establish promising avenues for continued exploration and fosters a sense of forward progress through the "fail fast, fail cheap" attitude [40,56], making them particularly economical at testing core concepts, basic assumptions, and user mental models [6].

Increase Low Fidelity Prototyping Value With Do-It-Yourself Design. Principles for fabrication were extracted from a study of the DIY movement in a previous effort [37], these principles can

be applied in prototyping to reduce cost and correspondingly increase relative value. These principles are aimed at reducing cost, time, and effort of fabrication while improving the outcome [37]. Two particular methods of DIY design that was prevalent in the case study were "hacking," which repurposes, modifies, and redeploy an existing product, and "basic craft," which employs tools, components, and materials that are readily available [37].

Use High Fidelity Prototypes to Test Finer-Level Features or Subsystems. Higher fidelity prototypes do not necessarily generate more value. High fidelity prototyping efforts have their strategic advantages and should be utilized as such. In particular, high fidelity physical prototypes are found to be most valuable when used to test finer level features or subsystems rather than big ideas [6]. Besides that, prototypes with higher fidelity representation also prove to lead to more accurate interpretations by third parties reviewing the design [57].

Be Especially Purposeful With Higher Fidelity Prototypes. Since high fidelity prototyping necessarily expends more resources, being purposeful with them is especially important. In general, a prototyping effort should answer a specific question [40] or resolve a unique design problem or opportunity [1]. Accordingly, to be economical, higher fidelity prototyping efforts should be matched by the level of detail of questions asked [7].

Augment Physical Prototyping With Other Media and Forms of Design Language. Augmenting physical prototypes with multimedia, such as videos and slides, can help make prototyping efforts more economical [8]. For example, virtual prototypes may
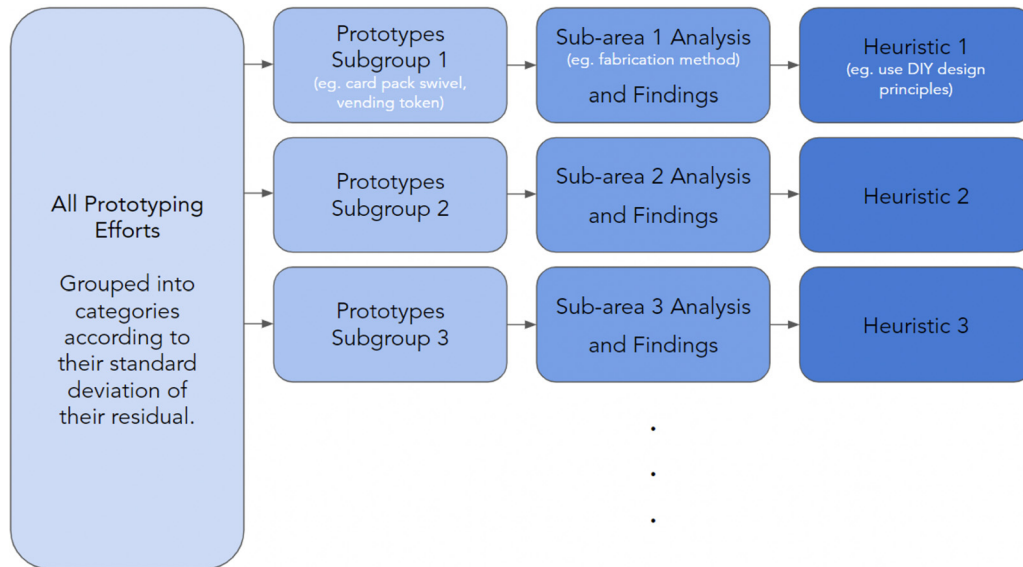
Fig. 20 Process of how heuristics are derived: All prototyping efforts are grouped into categories according to their standard deviation from the residual. Next, they are analyzed in their subgroup on a specific area of prototyping (e.g., fabrication method). The findings and insights the analysis in each subgroup then abstracted into a heuristic.

drastically lower costs [13] and sometimes can be made rapidly than physical prototypes [58], yielding roughly equal performance [13]. An example of this is the rendered prototype.

System Development, Additional Principles

Conduct Fundamental Tests. Utilize testing on the component level to identify fundamental phenomena and interactions that can lead to substantial cost savings downstream. The complexity of subsystem interactions in a system project gives rise to many possible failure modes and limitations when subsystems are re-integrated. By conducting simple tests, fundamental behavior can be understood, making it possible to identify a critical path early in the project and be confident of its behavior and efficacy when subsystems are integrated.

Prototype for Functionality Early. While it may be tempting to delay prototyping for functionality until later in the project, early tests can identify many important functional requirements that will resolve potential issues of subsystem design later in the development. Furthermore, it is possible to identify crucial design insights that will inform core requirements of subsystem design even with low fidelity prototypes. Therefore, it is important to prototype with as soon as you can achieve a functionally minimal viable concept.

Integrate Subsystems Early. It is important to integrate subsystems as early as possible, even if the higher prototyping costs or complexity of integration suggests otherwise. This is because many design flaws only surface when subsystems are re-integrated. Additionally, minor performances gaps in each subsystem typically will compound into dramatic consequences at the systems level when integrated. To prevent resources from sinking into unfruitful development at the partitioned subsystem level, integrate as early and regularly as possible.

Service Design, Additional Principles

Simulate Using Real Data. In order to get more out of mockup prototypes, incorporate testing with the end users; base tests on real data, take careful accurate measurements in order to ensure that observations are based on traceable sources. Make sure that real data are used for simulations, user interactions are supported,

and assumptions are checked and controlled rather than left to chance. A low fidelity prototype built upon real data can yield highly meaningful results, while high fidelity prototypes based on too many assumptions can result in few insights.

Analysis of Economies: Summary

The different categories of our data and how we analyzed and extracted prototyping principles from them are succinctly summarized in Tables 8–10 for the product, system, and service realms, respectively.

Generalization of Findings

The overlap in findings across product-system-service projects with regard to the chart morphology in the correlation between fidelity and value, trends in regional analysis, and prototyping principles validates and reinforces the generalizability of our research approach and findings. Many ethnographic studies may sometimes be susceptible to contextual or problem selection variance, which are known to impact project outcomes. Due to the high variance in project scope, field, and other contextual variables—an increased confidence in the results is supported by the evidence.

Limitations

The results, discussion, and findings in this study include some obvious caveats associated with the projects that were studied. For example, the extent to which value was extracted from prototypes depended not only on its fidelity but also on how it was tested with the users and clients. The biases of the users and clients—influenced by their background in design, company culture, and demographics regarding age, gender, race, and experience—were also not accounted for in this study. Notwithstanding these limitations, the results of our studies substantiate an approach to understanding prototyping economies and provide practitioners with useful heuristics for prototyping regardless of how they eventually decide to use their prototypes.

Several of the authors were involved in the design effort as well as the subsequent research. However, the authors who were on the design team were exposed to the research question only after the

Table 8 Discovery of heuristics, B2C Product
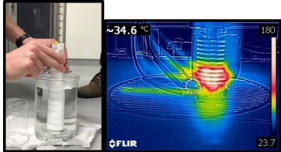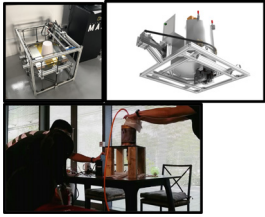
Category	Observation	Prototypes	Area of analysis	Findings	Proposed heuristic
Greater than 2 standard deviation above	Low fidelity, high value	Card pack swivel, LED vending token	Method of fabrication	Basic craft were utilized to make prototypes quickly, e.g., cardboard, marker, cut and glue.	Use Do-it-Yourself (DIY) design principles.
Greater than 1 standard deviation, But less than 2 standard deviation above	Low fidelity, low value	Cartoon QR Code	Purpose of prototype	Prototype was cheap but effectively tested a different core concept, revealing a new need.	Test core concepts with low fidelity prototypes.
	High fidelity, high value	Super sticker, Slap band slider, Hybrid wallet	Purpose of prototype	Prototypes were substantially differentiated and tested unique hypotheses.	Be especially purposeful with higher fidelity prototypes.
Within 1 standard deviation	Directly proportional	All other prototypes	Prototype dimensions	Prototypes with more dimensions exhibited higher value—correlation exists.	Aim for increased dimensionality.
		Smart student card, Adaptable token 2	Method of fabrication	Renders of prototypes exposed another dimension, e.g., visual realism	Augment with other media and forms of design language.
Greater than 1 standard deviation, But less than 2 standard deviation below	High fidelity, low value	Adaptable token 1, Fidget spinner, Rotating bezel coin	Purpose of prototype	Prototypes were created with many small details before testing big ideas like toys and loose items.	Use high fidelity prototype to test small details not big ideas.

Table 9 Discovery of additional heuristics through additional cases, system development

Greater than 2 standard deviation above	Moderate fidelity, high value.	Extrusion material testing, thermal analysis tests.	Purpose of prototype	Basic tests on material property revealed large number of latent needs, otherwise undiscovered.	Conduct fundamental tests.
				Valuable insights were gained through simple benchmarking of existing designs.	
Greater than 1 standard deviation, But less than 2 standard deviation below	High fidelity, low value.	Integration of the motion stage, CAD of integrated extrusion system, testing of wax extrusion system.	Order of prototyping	Hints of functional flaws were present at subsystem level but not addressed.	Prototype for functionality early.
				Subsystem iterations resulted in marginal performance and missed targets.	Integrate subsystems early.

design effort was completed. Therefore, a secondary data collection strategy was employed and it does not constitute a conflict of interest. It does help to ensure that the assessment of insights is more accurate through co-creation.

There may be potential for error in the measurement accuracy of time expended (our proxy for fidelity); however, since the region of interest is with regard to the residual line, the core emphasis of the paper is those features of a prototype that relate to value so small errors in time spent evaluation should not significantly impact this result.

Finally, as in some cases, the prototypes were presented in parallel to users; it may not be clear how a "negative" example may have impacted the perception of a "positive" example. The authors encourage the execution of controlled and replication studies to explore the core principles identified through this exploratory ethnographic research project. Finally, there is only one case study each per product service and system prototypes. While this demonstrates that common principles were observed across domains, it does not have the same meaning as a replication or the study of multiple problems in one domain would have in establishing confidence.

Conclusions and Future Work

Understanding the economies of design prototyping is of particular relevance to companies, designers, practitioners, and researchers. The work reported in this paper provides key research findings based on extensive empirical data from a FinTech B2C product project and supported by empirical data of a systems-development and service-design projects.

The section on insights (end of the service/system study summary section) directly provided an initial set of responses to the research questions. Insights are provided on how resources expended into prototyping translate into design value—a quantified coded value developed in this paper. These insights lead to prototyping strategies that can help design teams effectively reduce cost while increasing the efficacy of prototypes across varied design context. Foundations for the prototyping strategies are in the form of design prototyping principles, including aim for increased dimensionality; test core concepts with low fidelity prototypes; increase low fidelity prototyping value with DIY design; use high fidelity prototypes to test finer-level features or subsystems; be especially purposeful with higher fidelity prototypes; augment prototyping with other forms of design language; conduct fundamental tests in systems development; prototype for functionality early; integrate subsystems early; and simulate using real data for service design. The research was exploratory and uncovered a number of key avenues for continued empirical research in prototyping economies:

- What other ways can we measure fidelity to encompass a great degree of the time, cost, and effort that is invested in it?
- How can we measure the different dimensions of a prototype's fidelity consistently as McElroy's proposed?
- How does the gathering for design information change when we test prototypes with end users instead of clients?
- How do the demographic biases of designers, user, and clients affect the economies of prototyping?
- How do we further validate and deepen these results against more industry projects of a diverse nature?

Table 10 Discovery of additional heuristics through additional cases, service design

Greater than 2 standard deviation above	Low Fidelity, High Value.	Simulation of patient pathways and traffic flow.	Method of prototyping	When paired with real data, low fidelity simulation of patient pathways and traffic flow yield highly meaningful results.	Simulate using real data.

- How do we prototype to yield as many design information as possible?
- Besides fidelity, does the way we test prototypes with clients and users affect the design information we gain from them?
- What other variables can we use as the input and output when measuring the economies of prototyping?
- How do the type of prototypes—"implementation," "look and feel" and "role"—affect our understanding of their fidelity and economies?
- How else can we rate design information obtained from prototyping?
- How do we find the minimum subset of prototypes that we need to create to capture the maximum amount of design information?
- How much more value does prototyping bring to a concept?
- Does a prototype add more confidence in whether a requirement is met?

While there are key and archival results in this research, significant opportunities exist in studying the economies of prototyping in greater depth. These include substantial and ongoing efforts within the community to understand prototyping with the ultimate intention of distilling greater value for practitioners, educators, and researchers alike.

Acknowledgment

References

[1] Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., and Wood, K., 2017, "Design Prototyping Methods: State of the Art in Strategies, techniques, and Guidelines," Des. Sci., **3**, p. E13.

[2] Dow, S., and Klemmer, S., 2011, *Design Thinking: The Efficacy of Prototyping Under Time Constraints*, Springer, Berlin, pp. 111–128.

[3] Lauff, C., Kotys-Schwartz, D., and Rentschler, M. E., 2017, "What Is a Prototype?: Emergent Roles of Prototypes From Empirical Work in Three Diverse Companies," ASME Paper No. DETC2017-67173.

[4] Yang, M. C., 2005, "A Study of Prototypes, Design Activity, and Design Outcome," Des. Stud., **26**(6), pp. 649–669.

[5] Hall, R. R., 2001, "Prototyping for Usability of New Technology," Int. J. Hum.-Comput. Stud., **55**(4), pp. 485–501.

[6] McElroy, K., 2017, *Prototyping for Designers: Developing the Best Digital and Physical Products*, O'Reilly Media, Sebastopol, CA.

[7] Hartmann, B., 2009, *Gaining Design Insight Through Interaction Prototyping Tools*, Stanford University, Stanford, CA.

[8] Elverum, C., and Welo, T., 2014, "The Role of Early Prototypes in Concept Development: Insights From the Automotive Industry," Procedia CIRP, **21**, pp. 491–496.

[9] Womack, P. J., 2007, *The Machine That Changed the World*, Simon & Schuster, New York.

[10] Dyson, J., and Coren, G., 2001, *Against the Odds: An Autobiography*, Texere, London.

[11] Ries, E., 2011, *The Lean Startup: How Todays Entrepreneurs Use Continuous Innovation to Create Radically Successful Business*, Crown Publishing Group, New York.

[12] Camburn, B., Auernhammer, J., Sng, K., Mignone, P., Arlitt, R., Perez, B., Huang, Z., Basnet, S., Blessing, L., and Wood, K., 2017, "Design Innovation: A Study of Integrated Practice," ASME Paper No. DETC2017-68382.

[13] Camburn, B., Dunlap, B., Gurjar, T., Hamon, C., Green, M., Jensen, D., Crawford, R., Otto, K., and Wood, K., 2015, "A Systematic Method for Design Prototyping," ASME J. Mech. Des., **137**(8), p. 081102.

[14] Knapp, J., Zeratsky, J., and Kowitz, B., 2016, *Sprint: How to Solve Big Problems and Test New Ideas in Just Five Days*, Simon & Schuster, New York.

[15] Moe, R., Jensen, D., and Wood, K., "Prototype Partitioning Based on Requirement Flexibility," ASME Paper No. DETC2004-57221.

[16] Thomke, S., 2003, *Experimentation Matters: Unlocking the Potential of New Technologies for Innovation*, Harvard Business School Press, Boston, MA.

[17] Christensen, M. C., and Raynor, E. M., 2013, *The Innovator's Solution: Creating and Sustaining Successful Growth*, Harvard Business School Press, Boston, MA.

[18] Feldman, P. L., 2005, *Think, Play, Do: Technology, Innovation, and Organization by Mark Dodgson, David Gann, and Amon Salter*, Oxford University Press, Oxford, UK.

[19] Tom, K., and Littman, J., 2001, *The Art of Innovation: Lessons in Creativity from IDEO, America's Leading Design Firm*, Currency, New York.

[20] Martin, L. R., 2009, *The Design of Business: Why Design Thinking Is The Next Competitive Advantage*, Harvard Business Press, Boston, MA.

[21] Schrage, M., 2000, *Serious Play: How the World's Best Companies Simulate to Innovate*, Harvard Business School Press, Boston, MA.

[22] Verganti, R., 2014, *Design-driven Innovation: Changing the Rules of Competition by Radically Innovating What Things Mean*, Harvard Business Press, Boston, MA.

[23] Austin, R., and Devin, L., 2003, *Artful Making: What Managers Need to Know about Artists Work*, Prentice Hall, Upper Saddle River, NJ.

[24] Dahan, E., and Mendelson, H., 2001, "An Extreme-Value Model of Concept Testing," Manage. Sci., **47**(1), pp. 102–116.

[25] Simpson, J., and Weiner, E., 1989, "Economical, Oxford English Dictionary," Oxford Dictionaries, Oxford, UK, accessed Mar. 12, 2018. https://en.oxforddictionaries.com/definition/economical

[26] Charmaz, K., 2006, *Constructing Grounded Theory*, Sage Publications, Thousand Oaks, CA.

[27] Blessing, L., and Chakrabarti, A., 2009, *DRM: A Design Research Methodology*, Springer, London.

[28] Creswell, J., 2012, *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, Sage Publications, Los Angeles, CA.

[29] Yin, R. K., 2011, *Applications of Case Study Research*, Sage, Los Angeles, CA.

[30] Bhunia, P., 2017, "Accelerating Drive towards Cashless Society in Singapore – A Snapshot of Recent Initiatives." OpenGov Asia. Singapore, accessed Dec. 29, 2018. https://www.opengovasia.com/accelerating-drive-towards-cashless-society-in-singapore-a-snapshot-of-recent-initiatives/.

[31] Buxton, B., 2011, *Sketching User Experiences: Getting the Design Right and the Right Design*, Morgan Kaufmann, Amsterdam, The Netherlands.

[32] Tohidi, M., Buxton, W., Baecker, R., and Sellen, A., 2006, "Getting the Right Design and the Design Right," SIGCHI Conference on Human Factors in Computing Systems, (CHI '06), New York, pp. 1243–1252.

[33] Thomke, S., and Von Hippel, E., 2002, *Customers as Innovators: A New Way to Create Value*, Harvard Business Review, Brighton, MA.

[34] Gartzen, T., Brambring, F., and Basse, F., 2016, "Target-Oriented Prototyping in Highly Iterative Product Development," Procedia CIRP, **51**, pp. 19–23.

[35] Colhoun, J., Gentner, D., and Loewenstein, J., 2008, "Learning Abstract Principles Through Principle-Case Comparison," Cognit. Sci. Soc., pp. 1659–1664.

[36] Boroditsky, L., 2007, "Comparison and the Development of Knowledge," Cognition, **102**(1), pp. 118–128.

[37] Camburn, B., and Wood, K., 2018, "Principles of Maker and DIY Fabrication: Enabling Design Prototypes at Low Cost," Des. Stud., **58**, pp. 63–88.

[38] Dijk, L., Vergeest, J. S. M., and Horvath, I., 1998, "Testing Shape Manipulation Tools Using Abstract Prototypes," Des. Stud., **19**(2), pp. 187–201.

[39] Häggman, A., Tsai, G., Elsen, C., Honda, T., and Yang, M. C., 2015, "Connections Between the Design Tool, Design Attributes, and User Preferences in Early Stage Design," ASME J. Mech. Des., **137**(7), p. 071408.

[40] Neeley, L., Lim, K., Zhu, A., and Yang, M. C., 2013, "Building Fast to Think Faster: Exploiting Rapid Prototyping to Accelerate Ideation During Early Stage Design," ASME Paper No. DETC2013-12635.

[41] Houde, S., and Hill, C., 1997, "What Do Prototypes Prototype?," *Handbook of Human-Computer Interaction*, 2nd ed., Elsevier, Amsterdam, The Netherlands.

[42] Lim, Y., Stolterman, E., and Tenenberg, J., 2008, "The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas," ACM Trans. Comput.-Hum. Interact., **15**(2), p. 27.

[43] Otto, K., and Wood, K., 2001, *Product Design: Techniques in Reverse Engineering and New Product Design*, Prentice Hall, Upper Saddle River, NJ.

[44] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., and Wood, K. L., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," Res. Eng. Des., **13**(2), pp. 65–82.

[45] Stone, R., and Wood, K., 2000, "Development of a Functional Basis for Design," ASME J. Mech. Des., **122**(4), pp. 359–370.

[46] Stone, R., Wood, K., and Crawford, R., 2000, "A Heuristic Method for Identifying Modules for Product Architectures," Des. Stud., **21**(1), pp. 5–31.

[47] Macomber, B., and Yang, M., 2011, "The Role of Sketch Finish and Style in User Responses to Early Stage Design Concepts," ASME Paper No. DETC2010-48714.

[48] "Poehlmann, F., and Bestle, D., 2012, "Multi-Objective Compressor Design Optimization Using Multi-Design Transfer Between Codes of Different Fidelity," ASME Paper No. GT2012-68577.

[49] "Wang, J. X., Roy, C. J., and Xiao, H., 2018, "Propagation of Input Uncertainty in Presence of Model-Form Uncertainty: A Multifidelity Approach for Computational Fluid Dynamics Applications," ASCE-ASME J. Risk Uncertainty Eng. Syst., Part B: Mech. Eng., **4**(1), p. 011002.

[50] "Schemmann, C., Geller, M., and Kluck, N., 2018, "A Multi-Fidelity Sampling Method for Efficient Design and Optimization of Centrifugal Compressor Impellers," ASME Paper No. GT2018-75160.

[51] "Williams, M. A., and Alleyne, A. G., 2014, "Variable Fidelity Modeling in Closed Loop Dynamical Systems," ASME Paper No. DSCC2014-6159.

[52] Koelle, D., 1984, "The Transcost-Model for Launch Vehicle Cost Estimation and Its Application to Future Systems Analysis," Acta Astronaut., **11**(12), pp. 803–817.

[53] Mukaka, M. M., 2012, "Statistics Corner: A Guide to Appropriate Use of Correlation Coefficient in Medical Research," Malawi Med J., 24(3), pp. 69–71.

[54] Camburn, B., Arlitt, R., Perez, B., Anderson, D., Choo, P., Lim, T., Gilmour, A., and Wood, K., 2017, "Design Prototyping of Systems," 21st International Conference on Engineering Design (ICED17), Vol 3: Product, Services and Systems Design, Vancouver, BC, Canada, Aug. 21–25.

[55] Fu, K., Yang, M., and Wood, K., 2015, "Design Principles: The Foundation of Design," ASME Paper No. DETC2015-45157.

[56] Gerber, E., and Carroll, M., 2012, "The Psychological Experience of Prototyping," Des. Stud., **33**(1), pp. 64–84.

[57] Hannah, R., Joshi, S., and Summers, J., 2012, "A User Study of Interpretability of Engineering Design Representations," J. Eng. Des., **23**(6), pp. 443–468.

[58] Christie, E., Jensen, D., Buckley, R., Ziegler, K., and Crawford, R., 2012, "Prototyping Strategies: Literature Review and Identification of Critical Variables," ASEE Annual Conference and Exposition, San Antonio, TX, June 10–13, p. 25.1091.