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AN INVESTIGATION OF DESIGN REQUIREMENT VOLATILITY, RISK AND PRIORITY IN EARLY STAGE DESIGN PROJECTS

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ABSTRACT

In new product development, design requirements are a formalization of a product vision and can evolve substantially in the early stages of product design. This paper describes an empirical study of the relationships among design requirements volatility, risk, prioritization and the quality of design outcome in the context of a graduate level product development course for mid-career professionals. Among other findings, a pattern of decreasing risk of a design requirement, especially the risk of high priority requirements, was found to be a key predictor of success. The findings suggest the importance of managing design requirement risk in early stage design and the potential benefit of using risk and priority level of design requirements to monitor design project health.

INTRODUCTION

A set of design requirements is a description of the desired solution to a design problem [1]. A requirement specifies what the product must do or defines a quality that the product must have [2]. The benefits of good design requirements are twofold: in the short term, it ensures communication among all stakeholders, serving as a base for requirements evolution; in the long term it raises the likelihood that the "right" system will be built [3]. In particular, a survey of ~500 product managers found that one of the most frequently cited challenges in managing an engineering program were unclear, unstable or incomplete requirements. These can easily expose the design program to risk and thus lead to potential failure. At the same time, these managers felt that there were few strategies available to mitigate risks associated with design requirements [4]. Two reasons identified for this negative impact of poorly formulated requirements are volatility and unstable prioritization of a requirement [4].

In early stage design, some volatility of design requirements is to be expected as a design emerges, but too much volatility wastes resources in trying to address a moving target. Changing one requirement in a subsystem may trigger changes in other subsystems and thus can cost time and resources as the change propagates. Likewise, the priority of a requirement may change, suggesting that the team's vision of the design is unclear or evolving. Hauser and Clausing emphasize that customer needs cannot all be addressed by the design team, and that prioritizing needs is key to effective allocation of design resources [5]. This study offers an assessment of these two aspects of design requirements in the early, product-defining stages of the design process.

This paper presents a descriptive study that illustrates how prioritization and risk level of early stage design requirements evolve over time in a study of mid-career professional graduate students. This study observes how these aspects of requirements relate specifically to design outcome measures and addresses the following questions:

1. How do design requirement quantity and volatility relate to the outcome of design projects?

This question is underpinned by the idea that formulating more design requirements may indicate a more thorough consideration of the goals of a design and how to achieve those goals. However, too many requirements may be distracting and could dilute design teams' effort and resources. This study focuses on a small-scale design project, and the expectation is that there will not be a downside to having too many design requirements. It is

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expected that teams who generate more requirements will perform better [6].

Requirement changes are common in the early phases of design as requirements are formulated and evolve. However, too much change at this stage may make project management difficult. High requirement volatility may also reflect a lack of clarity about the goal of design. Thus the expectation is that high requirement volatility correlates with poorer project performance.

   2. How do design requirement prioritization and risk control relate to the outcome of these design projects?

It is anticipated that appropriate prioritization of requirements is important for the success of a project, as prioritization can guide designers' attention and effort. It's also key that there be a distribution of requirement priority - if all requirements were defined to be high priority then prioritization does not help the team decide where to best focus their efforts. The presence of low risk design requirements is anticipated to be linked to more successful projects since they are more likely to be achieved by the team. This study explores changes in requirements prioritization and risk level and their role in design performance.

PREVIOUS WORK

1. Design Requirements Formulation
The activities that make up requirements include gathering/eliciting requirements from stakeholders; analyzing and refining the requirements for completeness, consistency; determining what subset of the requirement should be addressed considering budget and time constraints; documenting the requirements; verifying the requirements conform to quality standards, and managing changes to requirement [3]. Via formulating design requirements, designers explore the problem-space of a design as well as the solution-space. It is necessary to keep a 'problem-finding' manner when forming design requirements [7].

Studies conducted with student designers suggested that it is important to continue capturing design requirements throughout the project. Those who had a higher number of final requirements were more likely to be successful because they were more likely to gain deeper understanding of the design problem at the end of the project [6]. In addition, it was found that writing good design requirements that are complete and detailed is key to the success of student design teams [8]. Also, the impact of requirement elicitation activity on the idea generation was investigated. However, no potential benefit of requirement generation in preliminary ideation was found with student designers [9].

In a protocol study of a design experiment within a laboratory setting, individual participants were asked to design a swivel mounted mechanism. Results showed that requirements are generated both during the task clarification phase and the conceptual design phase. The former is mainly from analysis of the assignment and constraints such as bill of materials and associated manufacturing information, while the latter is mainly from analysis of proposed designs [10].

Darlington, et al. explored the factors that influence the formulation of design requirements. After interviewing engineers and product managers in companies, they derived a model that attempts to identify and organize the chief factors that influence the design requirement development process and design requirement change [11]. Ten factors were identified, including 'design activity type', 'design requirement capture methodology', etc.

Models are created to describe and manage the requirement formulation process. Some of them have been widely adopted in industry, such as Quality Function Deployment [12] and Design Structure Matrix [13]. New tools have been built based on these and focus on specific perspectives of design requirement formulation. For example, Agouridas, et al. introduced the Motivational Rationale Traceability Matrix as a means to support stakeholder needs analysis and the corresponding derivation of design requirements [14]. Bonev, et al. combined several existing models and created a tool to facilitate product redesign and integrated product design based on existing product architectures [15].

2. Design Requirement Volatility
Requirements volatility is a concept that stems from requirements engineering, a subfield of software design and engineering. It refers to growth or changes in design requirements during a project's development lifecycle [16].

The influence of design requirement volatility is twofold. It is necessary to keep design requirements current throughout the design process and among design stakeholders. As designers gain more understanding of the design challenges and their ability to address the design problem, requirements need to be updated accordingly. However changes in requirements in one subsystem or the overall system may propagate to other requirements on different subsystems leading to possible increase in the project cost and lead-time, increasing complexity, and potential data lost.

Changes to the set of design requirements can spur dramatic effects on a product's development. Individual changes may not be by themselves expensive or time-consuming, but the cumulative effect can be substantial [17]. Managing the changes requires effort and may be inefficient from a project management point of view [18].

Models and tools have been developed specifically to describe and manage design requirement volatility. Ferreira, et al. introduced a model to simulate the complex impact of design requirement changes on a software project [19]. Morkos, et al. used higher order a design structure matrix to predict requirement change propagation [18]. Koh, et al. developed a method to assess the effects of requirement changes based on the House of Quality and Change Prediction Method [20].

METHOD
Data for this study was gathered from a semester-long graduate-level design course at a US university in two successive years, 2013 and 2014. Students taking this class were mid-career professionals with at least a Bachelor's degree and an average of five to ten years engineering and technology experience in industry. They worked in teams of about five, identifying product opportunities and designing and delivering a working prototype. Fig. 1 shows a representative prototype created in the course, which is a backpack that converts to a laptop desk.

In year 2013, there were 62 students and 11 teams. In year 2014, there were 34 students and 7 teams. The course objectives

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and syllabus of the course remained the same over the years. Each team was given a budget of $800 for their projects.

Fig. 1 Example of proof-of-concept prototypes developed in the course (a backpack converts to laptop desk)

The milestone events of the course can be found in the timeline in Fig. 2. In both years, product contracts were collected on a team basis after each team selected their concepts from multiple alternatives to a final design. Seven product contracts were collected from each team in both years. The time periods (by week) in which product contracts were collected are marked from A to G. In addition to the product contract, user interaction questionnaires and prototyping questionnaires were completed by individual students on a weekly basis to track details of how they interacted with potential users and details of building their prototypes.

At the end of the semester, teams presented their projects to a panel of judges (both practitioner and academic) who evaluated the projects.
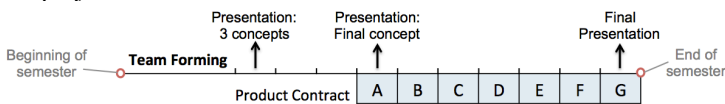

Fig. 2 Course time line (indicating time periods in which product contracts were collected)

1. Design Requirements: the Product Contract

The product contract is a simplified set of design requirements used specifically in this course and builds on design requirements as described in the course textbook [21]. Formulating a contract helps the students clarify the features of their products, and set goals for their design and their final prototypes. Each design team was asked to formulate a product contract in a shared Google Docs spreadsheet for their initial design, and then update the contract in a new sheet on a weekly basis to reflect changes in their design.

Fig. 3 shows a product contract for a sports wristwatch that was given to the teams as an example. Each design requirement consists of three parameters: the *Customer Need* reflects the qualitative user need satisfied by the design requirement, such as long power life; the *Product Attribute* specifies the unit of measure that can satisfy the user's need (i.e. time or weight); and the *Engineering Specification* sets values for the product attribute (i.e. "At least 2 years of battery life").

In addition, teams were asked to assess the priority of each design requirement and the risk level of the requirement.

Priority indicates how critical a requirement is to a successful design. It has three levels, high, medium and low. High priority requirements were deemed by the team to be of more importance to the success of their project, while low priority requirements were less critical. Teams were asked to be thoughtful in assessing prioritization – not every requirement could be "high" priority or else the prioritization would be less meaningful.

Risk indicates the level of confidence of the team that a particular design requirement could be met in the prototype design. Teams noted which requirements were they felt would be most difficult to meet, either in their design or in the fabrication of their prototypes. For example, one team was designing a baby monitor system to allow a parent to see and hear their infant from another room in their home. This baby monitor's main source of innovation was its form factor rather than its technology. In this case, the industrial and mechanical design would be the high risk aspects, while technology would be low. High risk requirements were assumed to be less likely to be realized, while the low risk requirements are generally easier to meet. Risk also varies on three levels.

Teams were also asked to categorize the changes they made to design requirements each time they made an update. Three types of design requirement changes were defined (see Fig. 3):

Add - when an entirely new requirement is added to the contract.

Delete - when an existing requirement is removed from the contract.

Modify - when an existing requirement is altered in description, specification, priority or risk.

All three kinds of design requirement changes were tracked as evidence of design requirement volatility.

Requirement Quantity and *Requirement Change Rate* of each team for each team were later analyzed to assess their potential role in project success.
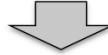
Requirement Quantity - the number of design requirements in a product contract at a given point in time. Teams were free to generate as many or few requirements as they deemed appropriate to define their product vision. However, the examples shown in class were all in the range of 7-10 requirements.

Requirements Change Rate - the ratio of the total number of design requirement changes (including add, delete and modify) over the requirement quantity for each time period. *Requirement change rate* is a measurement of requirement volatility. The more a set of design requirements changes over time, the more volatile it is.

Three ratios were defined to evaluate the proportion of the number of high priority requirements and the high risk requirements within the product contract. These ratios indicate which requirements are most critical for the team to meet and are most challenging to meet.

High priority (HP) ratio – the number of high priority requirements over the total number of design requirements.

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Consumer Needs	Product Attribute	Engineering Specifications	Priority	Risk
Comfortable	Dimensions	Case Diameter < 35 mm	High	Low
		Case Thickness < 9 mm		
		Band Length < 250 mm		
		Band Width < 20 mm		
Long Lasting Power	Life of Battery	> 2 years	Low	Medium
Light Weight	Weight	< 3 oz.	Medium	Medium
Modern Appearance	Styling	Panel of Expert Rate 4/5	Low	Low
Easy to clean	Materials	Plastic, Metal	Medium	High
Water Resistant	Pressure Resistance	Water Depth Resistance > 100 m	Low	High

Consumer Needs	Product Attribute	Engineering Specifications	Priority	Risk	
Comfortable	Dimensions	Case Diameter < 35 mm	High	Low	
		Case Thickness < 9 mm			
		Band Length < 250 mm			
		Band Width < 20 mm			
Long Lasting Power	Life of Battery	> 2 years	Low	Medium	
Light Weight	Weight	< 3 oz.	Medium	Medium	
Modern Appearance	Styling	Panel of Expert Rate 4/5	Low	Low	→ Delete
Easy to clean	Materials	Plastic, Metal	Medium	High	
Water Resistant	Pressure Resistance	Water Depth Resistance > 60 m	Low	High	→ Modify
Easy to Set Time and	Time	Set Up Time < 10s	Low	High	→ Add

Fig. 3 Changes in product contract of an imaginary sport watch

High risk (HR) ratio – the number of high risk requirements over the total number of design requirements.

High risk to high priority (HR-HP) ratio – the number of requirements that is both high risk and high priority to the number of high priority requirements, which is the ratio of high risk requirement within high priority ones.

The three ratios were evaluated on a team basis for product contracts of each time period.

2. Product Outcome Evaluation

At the end of the project, the products were evaluated by the previously mentioned panel on a number of measures: how well the product meets user needs, the quality of prototype's craftsmanship, and the products' potential market performance. The panel first rated the teams individually, then convened and discussed the performance of each team to achieve group consensus. Two rankings of the products' success were given each year, one according to the average number of the individuals' ratings (which will be called individual ranking later on), the other based on the panel discussion (called panel ranking).

For each year, there were in total nine judges in the panel whose ratings were finally taking into account. There was one more judge each year that could not make the entire final presentation thus rated only some but not all the teams. Their ratings were not used to evaluate the product success in this paper.

RESULTS

1. Requirement Quantity and Volatility

The number of requirements in a product contract varied from 6 to 21 in year 2013 and 6 to 18 in year 2014. The average number of requirement and its standard deviation of each team are plotted in Fig. 4. There was only one team in each year that generated more than 15 design requirements. All other teams had lower quantities of requirements.

Of the three kinds of requirement changes, *Modify* was the majority. Modified requirements consisted of 64% of the changes in year 2013 and 76% of the changes in year 2014.

When new requirements were added, it was often because new user needs were discovered or new ways to address a customer needs were brought up. These new requirements might evolve in later periods of time or might be later deleted.

When a requirement was deleted, possible causes could be the designers found it not critical for addressing user needs (low priority), or too difficult to achieve within the time-scope and resources of the project (high risk).

When a requirement was modified, it could either be the *Customer Needs, Product Attribute, Engineering Specification, Priority level* or *Risk level* that changes. The changes of *Customer Needs* reflected an improved understanding of how the product will serve users. The changes of *Product Attribute and Engineering Specification* represented better or more realistic solution to satisfy the user needs. When the *Priority level* changes, it was usually because the designers' shifted their focus of the product main feature. Changes of *Risk level* usually resulted from designers gaining understanding of how difficult or easy to realize a requirement after research, experimenting and prototyping.

The fact that a majority of requirement changes were modification indicates that there were not much drastic changes to the design concepts introduced over time. The accumulation of different kinds of requirement changes for each team can also be found in Fig. 4.

The cumulative number of requirement changes was found to be correlated with the requirement quantity (Pearson correlation $\rho = 0.88$, p-value $= 3.3\times10^{-4}$ for 2013, $\rho = 0.85$, p-value $= 0.015$ for 2014), which means the teams with more requirements were more likely to have more absolute number of requirement changes. However between the requirement quantity and requirement change rate, less significant correlation was found in year 2013 (Pearson correlation $\rho = 0.63$, p-value $= 0.02$), and no significant correlation was found in year 2014 ($\rho = 0.002$, p-value $= 0.997$). Based on this, it was determined that the absolute number of requirement changes is confounded with the requirement quantity, and requirement change rate is a better representation of the requirement volatility. The average *Requirement Change Rate* of each team can be found in Fig. 4.
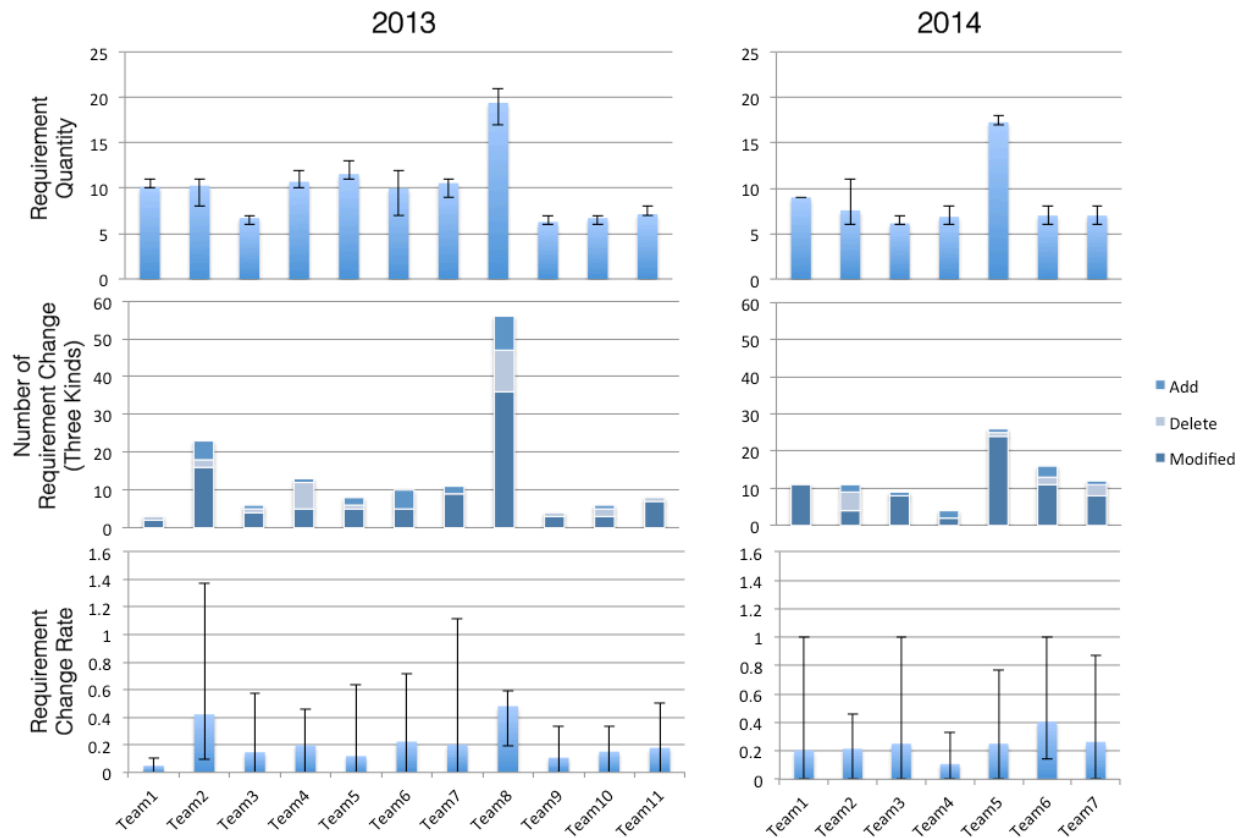
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Fig. 4 Requirement quantity (top, time-average with max and min value), accumulation of three kinds of requirement change (middle), and requirement change rate (bottom, time-average with max and min value) of each team

2. Product Outcome Ranking

The final team projects were first rated and then ranked. The individual ranking and panel ranking for both years are listed in Table 1. There were minor adjustments when the panel gathered together and reach a consensus of ranking via discussion, thus there are some differences between the individual ranking and the panel ranking. However the differences are small and the two rankings match each other well. Spearman correlation between the two rankings gave that $\rho = 0.93$ (p-value = 0.0067) for 2013 and $\rho = 0.80$ (p-value = 0.0052) for 2014.

It was observed that the ratings given to the same team by different panel members were not consistent, which perhaps reflects the diversity of opinion individuals from different disciplines (engineering, design, marketing). The Pearson correlation rho ranged from 0.02 in year 2014 to -0.55 in year 2013, which means that panel members had different opinions on the success of each product. However, all judges agreed on the top performing and worst performing teams (see [22] for more explanation). Thus we further divided all teams into two categories: the top tier teams and the bottom tier teams, and compared the performance of teams between these two groups. The lines between top tier and bottom tier were drawn below the median of ranking. In this way, we have fairly equal amount of teams in both tiers. Also the teams above and beneath the lines in both ways of ranking are the same.

Later in this paper, the two rankings will be compared with requirement quantity, change rate, risk and priority ratios.

Spearman correlations will be calculated between the ranking and design requirements. ANOVA will be conducted between results of top tier and bottom tier teams.

Table 1 Product success evaluation results

2013

Rank	Individual	Panel	
1	Team 1	Team 10	
2	Team 10	Team 9	
3	Team 8	Team 1	**Top Tier**
4	Team 3	Team 6	
5	Team 9	Team 8	
6	Team 6	Team 3	
7	Team 2	Team 7	
8	Team 11	Team 11	**Bottom Tier**
9	Team 5	Team 2	
10	Team 7	Team 4	
11	Team 4	Team 5	

2014

Rank	Individual	Panel	
1	Team 5	Team 5	
2	Team 2	Team 2	**Top Tier**
3	Team 1	Team 6	
4	Team 6	Team 1	
5	Team 4	Team 4	
6	Team 3	Team 7	**Bottom Tier**
7	Team 7	Team 3	

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3. Relate Requirement Quantity and Change Rate to Project Success

Fig. 5 shows the requirement quantity and requirement change rate of top tier teams and bottom tier teams for each time period.

Requirement quantity of each team was fairly constant across all time periods. There were no significant differences between the requirement quantity of the top and bottom tier teams. Though the average requirement quantity of the top tier teams is consistently higher than the bottom tier team in year 2014, the ANOVA results showed the difference between them appeared to be insignificant.

Spearman correlations were also calculated between requirement quantity and both the individual and panel rankings of the product outcome (see Table 2). At a significance level of 0.05, there were no significant correlations between product outcome and requirement quantity.

We found that both of the teams with more than 15 requirements in each year were in the top tier. However, stating more design requirement generally didn't result in better performance. Teams who had fewer requirements didn't necessarily perform worse.

Requirement change rate was the highest when teams made their first iteration of the product contract. This was consistent with the milestones for the project, as teams explored potential design concepts in these early phases before settling on one direction to pursue in the later phases.

ANOVA did not show significant differences in the requirement change rate between the top and bottom tier teams for both years. Spearman correlation also did not show significance. Contrary to what was expected, the requirement change rate was not found to significantly correlate with the design outcomes.
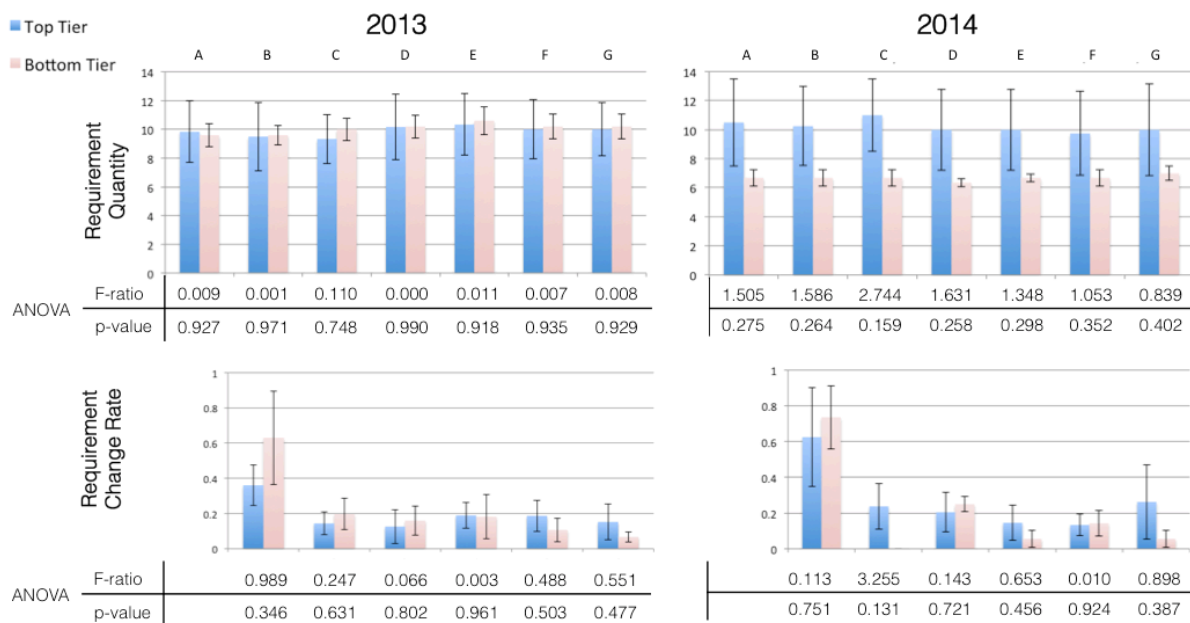

Fig. 5 Comparison of requirement quantity and requirement change rate between top tier teams and bottom tier teams for both year 2013 and 2014. ANOVA results included.

Table 2 Spearman correlation between the project success ranking (both individual ranking and panel ranking) and the requirement quantity, requirement change rate respectively.

			2013							2014						
	Time Periods		A	B	C	D	E	F	G	A	B	C	D	E	F	G
Number of Requirements	Individual Ranking	rho	-0.252	-0.278	-0.368	-0.348	-0.269	-0.234	-0.185	0.730	0.730	0.775	0.630	0.473	0.593	0.491
		p-value	0.454	0.408	0.266	0.294	0.425	0.488	0.586	0.081	0.081	0.051	0.152	0.289	0.179	0.268
	Panel Ranking	rho	-0.496	-0.499	-0.470	-0.556	-0.454	-0.428	-0.370	0.674	0.674	0.793	0.593	0.509	0.519	0.327
		p-value	0.121	0.118	0.145	0.076	0.161	0.190	0.263	0.124	0.124	0.041	0.179	0.249	0.245	0.475
Requirement Change Rate	Individual Ranking	rho		-0.151	-0.198	-0.134	0.135	0.019	0.114		-0.334	0.571	-0.321	0.059	-0.270	0.335
		p-value		0.658	0.560	0.695	0.692	0.956	0.739		0.471	0.200	0.498	0.905	0.551	0.476
	Panel Ranking	rho		-0.137	-0.097	-0.416	-0.167	0.019	0.005		-0.408	0.749	-0.429	0.296	0.090	0.374
		p-value		0.688	0.778	0.203	0.623	0.956	0.988		0.371	0.076	0.354	0.524	0.857	0.419

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4. Relate Requirement Risk and Priority to Project Success

Each team's requirement risk and priority ratios were calculated for each time period and the results were compared between the top tier teams and the bottom tier teams (see **Fig. 6**). ANOVA was conducted to evaluate the differences between the top and bottom tier teams. Significant differences at p<=0.05 were highlighted. Data from the two years did not follow exactly the same pattern, but did share some common features and trends.

High priority ratio. In 2013, the top tier teams had a higher average HP ratio. The difference between the two tiers was found to be significant at the last product contract. In contrast, the bottom tier teams had higher average high-priority requirement ratio in year 2014. However this difference was not found to be significant in any product contracts. Though these results are not consistent with each other, there is a similar trend for both years that the high priority requirement ratios of the top tier teams increased over time. Also we can observe that in year 2014, bottom tier teams constantly had large HP ratios with averages larger than 0.6, which implies that they might not have identified the most important requirements thus did not prioritize their requirements effectively.

High risk ratio. The average values of HR for the top tier teams were consistently lower than that of the bottom tier teams, in both year 2013 and 2014. This difference was found to be significant towards the end. In both years, the top tier teams' HR ratio decreased towards the end of the project. However, that of the bottom tier teams' increased in year 2013. Though it also decreased in year 2014 for the bottom tier teams, it didn't decrease as fast as top tier teams'.

High risk-High priority ratio. Top tier teams also had lower HR-HP ratios than the bottom tier teams in year 2013 and the difference was significant in almost all the time periods. Though ANOVA doesn't indicate a difference to be significant in year 2014, we can see that the upper tier teams do have higher average HR-HP ratios for all time periods. Similar to the HR ratio, we again observe that this ratio decreases towards the end of the project in top tier teams, however we do not see a similar trend in bottom tier teams.

The priority and risk ratios were also correlated with the individual and panel rankings (Spearman correlation coefficients and p-values, see Table 3). Significant correlations results were highlighted. The correlation results consist with the ANOVA results above.

The correlation coefficients between the HP ratio and ranking are positive in year 2013, meaning the better-performing teams also had more high priority ratio requirements. However it was quite the opposite for year 2014, where the correlation coefficients for the high priority ratio and ranking are all negative. All these correlations were not significant except the last time period of year 2013.
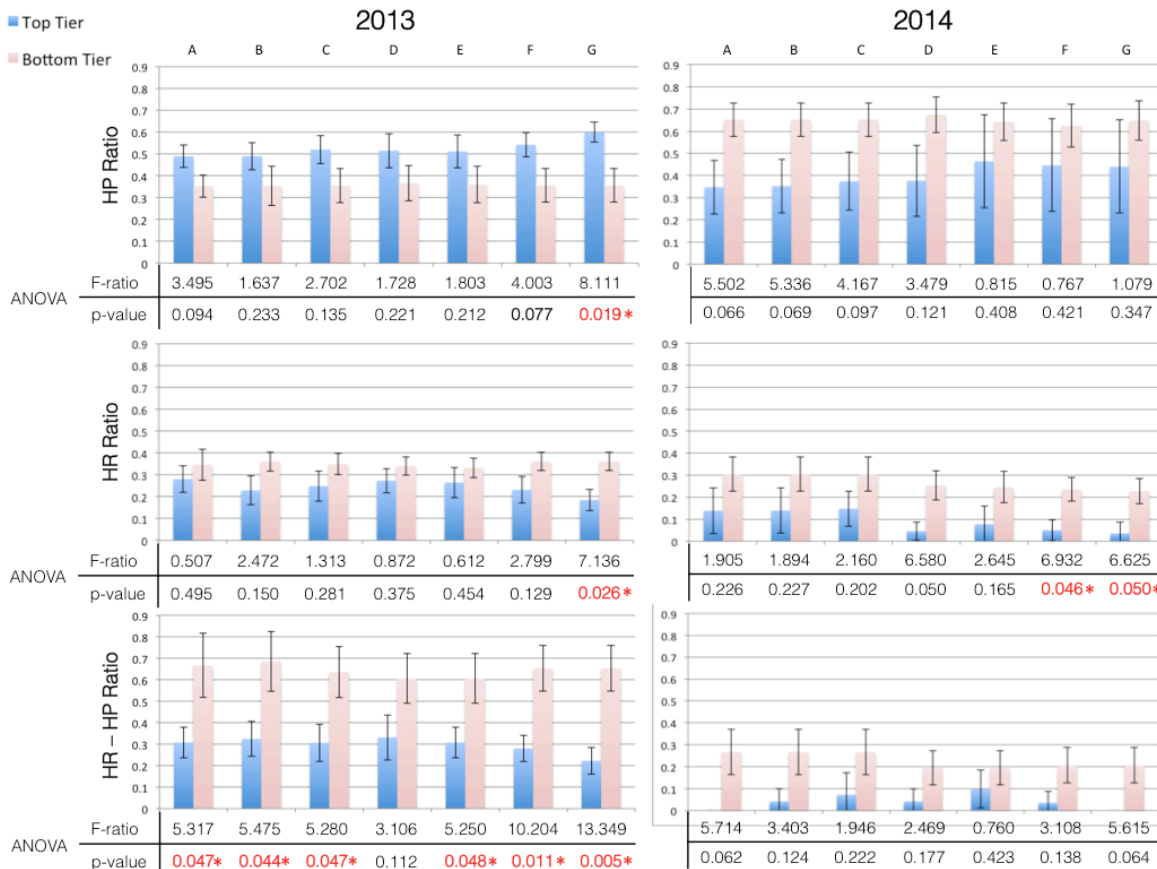

Fig. 6 Comparison of high priority (HP), high risk (HR), and high risk – high priority (HR-HP) ratios between top tier teams and bottom tier teams for both year 2013 and 2014. ANOVA results included (significance level α = 0.05)

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Table 3 Spearman correlation between the project success ranking (both individual ranking and panel ranking) and the high priority ratio, the high risk ratio, the high risk to high priority ratio respectively (significance level $\alpha = 0.05$)

			2013							2014						
		Time Periods	A	B	C	D	E	F	G	A	B	C	D	E	F	G
HP Ratio	Individual Ranking	rho	0.403	0.233	0.402	0.251	0.273	0.442	0.582	-0.757	-0.757	-0.571	-0.487	-0.360	-0.378	-0.357
		p-value	0.219	0.490	0.221	0.457	0.417	0.174	0.060	0.057	0.057	0.200	0.271	0.429	0.406	0.444
	Panel Ranking	rho	0.458	0.384	0.479	0.342	0.345	0.469	**0.645**	-0.577	-0.577	-0.429	-0.360	-0.216	-0.306	-0.321
		p-value	0.157	0.243	0.136	0.304	0.298	0.145	**0.032***	0.187	0.187	0.354	0.426	0.640	0.512	0.498
HR Ratio	Individual Ranking	rho	-0.106	-0.183	0.202	0.257	0.223	-0.246	-0.469	0.324	-0.360	-0.286	-0.764	-0.559	-0.764	**-0.823**
		p-value	0.758	0.589	0.552	0.446	0.509	0.466	0.145	0.477	0.429	0.556	0.062	0.206	0.062	**0.033***
	Panel Ranking	rho	-0.101	-0.330	0.055	0.073	0.114	-0.342	-0.424	0.432	-0.216	-0.143	-0.673	-0.432	-0.673	-0.674
		p-value	0.768	0.321	0.872	0.830	0.739	0.304	0.194	0.327	0.640	0.783	0.108	0.326	0.108	0.114
HR-HP Ratio	Individual Ranking	rho	-0.243	-0.369	-0.377	-0.303	-0.405	-0.583	**-0.703**	0.060	-0.339	-0.296	-0.296	-0.356	-0.374	-0.668
		p-value	0.472	0.265	0.253	0.364	0.217	0.060	**0.016***	0.057	0.057	0.271	0.271	0.429	0.406	0.444
	Panel Ranking	rho	-0.434	-0.548	-0.556	-0.483	-0.538	**-0.611**	**-0.635**	0.179	-0.179	-0.158	-0.158	-0.094	-0.197	-0.490
		p-value	0.183	0.081	0.075	0.133	0.088	**0.046***	**0.036***	0.187	0.187	0.426	0.426	0.640	0.512	0.498

The correlation coefficients between the HR ratio are negative at the last time periods for both year, which means better performed teams tended to have fewer high risk requirements towards the end of the project. However the relation between HR ratio and the performance ranking doesn't have a consistent pattern in the earlier time periods.

The correlation results between the HR-HP ratio and the rankings hold the best consistency between two years and across different time periods. The correlation coefficients are almost always negative (except the first time period for year 2014), suggesting that the teams whose high priority requirements were also low risk tended to perform better.

A preliminary analysis of the prototyping and user interaction questionnaires revealed that, the best-performing team of 2014 used their product contracts as a reference to their plan of building prototypes – they tried to make prototypes for the high priority requirements, and once they proved that the requirement was met, the risk of the requirement could be reduced. They had an increasing HP-HR ratio in the first half of the design process, since more problems were revealed during the exploration. But in the second half of the process their HP-HR ratio decreased continuously. It is assumed that this strategy contributed to their project success.

5. Evolution of Requirements' Prioritization and Risk Level

In the previous session, we found the better-performing teams tend to have fewer high-risk requirements. Also we observed the trend of that better-performing teams tend to reduce the risk level of their requirement. However the analysis did not tell us what kind of changes of the requirements lead to this result: were the high risk requirements abandoned? Were low-risk requirements added to the product contracts? Or were requirements originally labeled as high risk modified to be lower risk? In this section, we address these questions by investigating the changes of priority level and risk level of all requirements.

Fig. 7 plots the requirements' priority and risk level together, in which the x-axis represents the risk level and the y-axis represents the priority level. We grouped the top tier and bottom tier teams of each year and plotted the risk and priority levels of the first and last product contracts. Each dot represents one design requirement. In addition, we distinguished the sources of changes of requirements' risk and priority level. The changed requirements (only the requirements whose priority level or risk level were changed) were marked with green diamond dots; the added requirements were marked with blue squire dots; the deleted requirements with red crossing dots. The unchanged requirements were the yellow circles. Requirements which changed, but the risk and priority level of which didn't changed were treated as unchanged here.

From the plots it can be seen that the top tier teams in both years had more changed requirements than added or deleted requirements while the bottom tier teams made fewer changes on the requirements' risk or priority level. Also, the top tier teams' tendency to reduce high-risk requirements is clear. Most of the high risk requirements in the first product contract were either eliminated or changed to lower risk level in these teams. In addition, the majority of the requirements that were added later on had low risk. But for the bottom tier teams, not many high-risk requirements were eliminated or changed to lower risk. Instead, in year 2014, the bottom tier teams changed some requirements' risk to the high level in the end. Reducing high risk - low priority requirements and increasing the high priority - low risk requirements were the common activities that shared among the top tier teams. Such behaviors was not observed in the bottom tier teams.

DISCUSSION

To answer the two questions brought up at the beginning of this paper:

1. How do design requirement quantity and volatility relate to the outcome of these design projects?
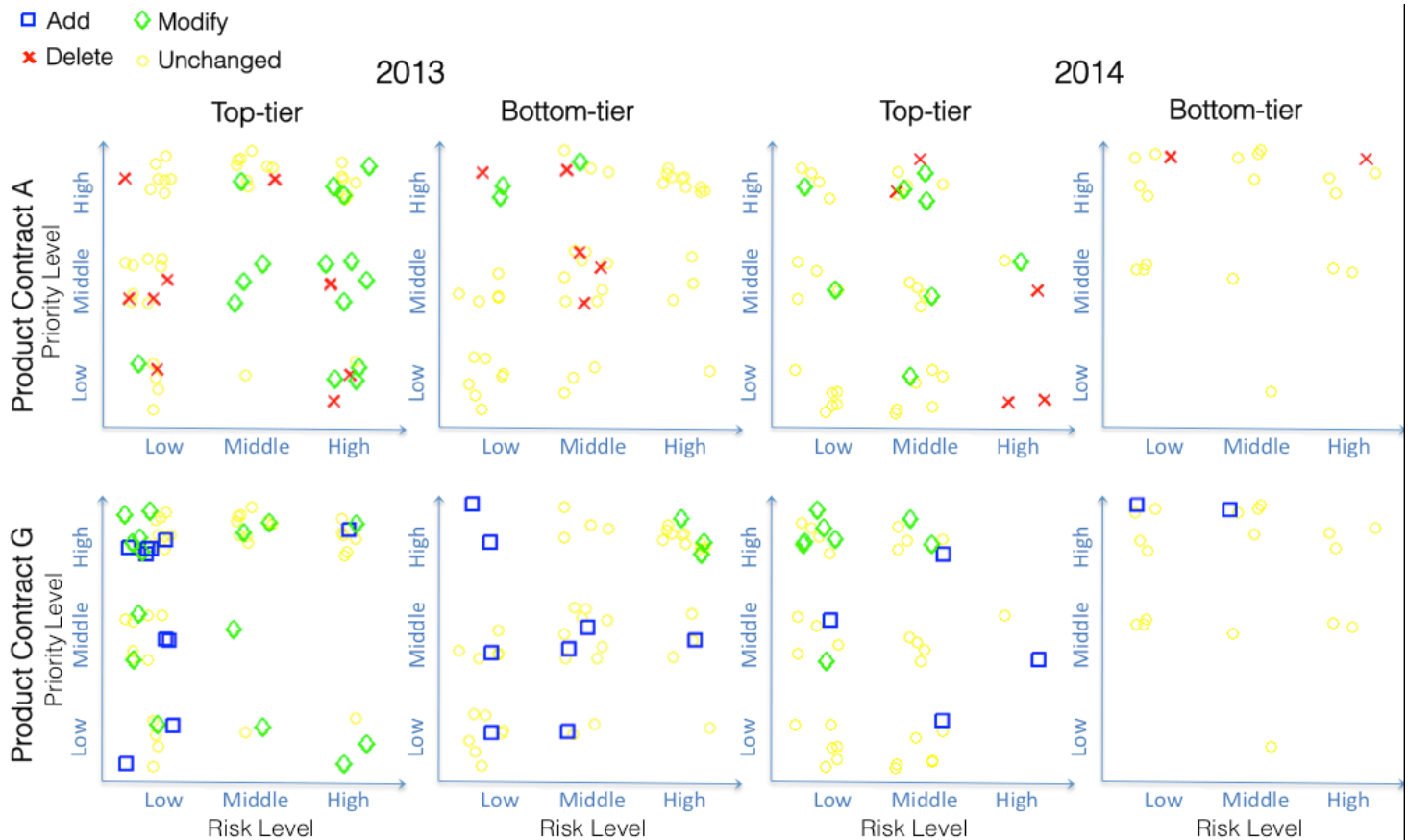
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Fig. 7 The prioritization and risk level of requirements for the first (top) and last (bottom) product contracts

Requirement quantity was not found to be significantly correlated with the project success. Even though the teams with the most design requirements in both years performed well, other teams in the top tier did not necessarily have more requirements than the bottom tier teams.

This is not consistent with a previous study which found requirement quantity to be positively correlated with design outcomes in student projects [6]. However there was limited variation in requirement quantity among teams (except the two teams with the most requirements), the conclusion here is not strong.

Requirement change rate (volatility) was also not found to be linked to design outcome. In these projects, managing requirement changes required limited effort from the teams. Thus it's not surprising that we didn't observe the down side of high volatility. In addition, requirement change rates were found decrease quickly for almost all teams, suggesting even the teams with high requirement change rate had a relatively stable product contract and design requirements converged relatively fast. On the other hand, successful products were not found to be necessarily related to a high requirement change rate. Some top tier teams generated "good" design requirements early in the project, with the requirements addressed both the user needs and the project scope. Even though these teams didn't adjust their requirements significantly, their products still performed well.

Another possible reason that we don't see significant correlations between requirement quantity, volatility and project success in this study is, different teams had design projects in

different area and with different complexity. How many requirements should be defined and how often did they change can be influenced by the design projects themselves.

2. How do design requirement prioritization and risk control relate to the outcome of these design projects?

The results suggest that controlling the risk of design requirement plays an important role in design outcome, especially the risk of high priority requirements. The better-performing teams usually had lower high risk (HR) ratio and lower high risk to high priority (HR-HP) ratio. In addition, these two ratios decreased towards the end of the design process in these better performing teams. The high priority ratio was not found to have significant links with the product outcome. In fact, the high priority ratio of both years had the opposite profiles. However, top-performing teams were observed to have an increasing HP ratio over time while bottom tier teams had a constant HP ratio. The bottom tier teams in year 2014 tended to have more high priority requirements but were perhaps unable to address them adequately. Whether these high priority requirements were actually realized in the proof-of-concept prototypes would be a valuable question to explore in a future study.

Some patterns were observed within the top tier teams that they utilized the product contracts to refer to their progress of the projects and to control the risk level of the design. The preliminary analysis of the changing of priority and risk level showed that, the top tier teams were more active in adjusting the

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risk and priority level of their design requirements while the bottom tier teams did much less modification of the risk and priority level of existing requirements. This underlines the value of managing the risk and priority level of product requirements.

CONCLUSIONS AND FUTURE WORK

This study investigated design requirements generated by mid-career professional student designers in a semester-long design course. It focuses on investigating design requirement changes from multiple aspects: the requirement volatility, prioritization and risk level.

The analysis of the relationship between the quantity of design requirement changes and project outcome did not tell us how requirement volatility influences product success. However, the results of this study show evidence that reducing the risk of design requirements is linked to the success of the design project.

The results suggest that, in engineering and product design classes, it may be helpful for the student to track the risk and prioritization with formal documentation and use it to monitor their design progress. If there are too many high-risk requirements, especially too many of the high-priority requirements have high risk level, it may worth considering how to reduce the risk level of these requirements or how to substitute them with lower risk requirements in the aim of delivering a better final design. Future work should consider how such tracking may be used in an industrial setting.

This current study is quantitative and focuses on comparing the performance of top tier and bottom tier teams. However a more detailed qualitative study with not only product contracts, but also the other materials we collected such as the prototyping and user interaction questionnaires may expose us to more qualitative knowledge of how the design requirements evolved, the reason behind how they changed, and how they led to different performance of the teams.

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REFERENCE

[1]   M. J. Darlington and S. J. Culley, "Current Research in the Engineering Design Requirement," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 216, no. 3, pp. 375–388, Jan. 2002.

[2]   J. Robertson, Suzanne Robertson, *Mastering the Requirements Process: Getting Requirements Right*. Addison-Wesley, 2012.

[3]   A. M. Davis and D. Zowghi, "Good Requirements Practices are Neither Necessary nor Sufficient," *Requir. Eng.*, vol. 11, no. 1, pp. 1–3, Oct. 2004.

[4]   J. Oehmen, B. W. Oppenheim, D. Secor, E. Norman, E. Rebentisch, J. A. Sopko, M. Steuber, R. Dove, K. Moghaddam, S. McNeal, M. Bowie, M. Ben-Daya, W. Altman, and J. Driessnack, *The Guide to Lean Enablers for Managing Engineering Programs*. 2012.

[5]   J. R. Hauser and D. Clausing, "The House of Quality," *Havard Bus. Rev.*, 1988.

[6]   J. Summers, B. Morkos, and S. Joshi, "Requirements Evolution: Relating Functional and Non-Functional Requirement Change on Student Project Success," in *ASME International Design Engineering Technical Conferences*, 2014.

[7]   M. Suwa, J. Gero, and T. Purcell, "Unexpected Discoveries and S-invention of Design Requirements: Important Vehicles for a Design Process," *Des. Stud.*, 2000.

[8]   J. D. Summers, "Tracking Project Health Using Completeness and Specificity of Requirements: A Case Study," in *ASME nternational Design Engineering Technical Conferences*, 2014.

[9]   S. Joshi and J. D. Summers, "Impact of Requirements Elicitation Activity on Idea Generation: A Designer Study," in *ASME International Design Engineering Technical Conferences*, 2014.

[10]   A. Chakrabarti, S. Morgenstern, and H. Knaab, "Identification and Application of Requirements and their Impact on the Design Process: a Protocol Study," *Res. Eng. Des.*, vol. 15, no. 1, pp. 22–39, Mar. 2004.

[11]   M.J. Darlington and S.J. Culley, "A Model of Factors Influencing the Design Requirement," *Des. Stud.*, vol. 25, no. 4, pp. 329–350, Jul. 2004.

[12]   Y. Akao, *Quality Function Deployment: Integrating Customer Requirements into Product Design*. Productivity Press, Cambridge, MA, USA, 1990.

[13]   D. V. Steward, "The Design Structure System: A Method for Managing the Design of Complex Systems," *IEEE Trans. Eng. Manag.*, vol. EM-28, no. 3, pp. 71–74, 1981.

[14]   V. Agouridas, H. Winand, A. McKay, and A. de Pennington, "Early Alignment of Design Requirements with Stakeholder Needs," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 220, no. 9, pp. 1483–1507, Jan. 2006.

[15]   M. Bonev, M. Wörösch, D. Hauksdóttir, and L. Hvam, "Extending Product Modeling Methods for Integrated Product Development," in *19th International Conference on Engineering Design*, 2013, pp. 219–228.

[16]   S. Ferreira, D. Shunk, J. Collofello, G. Mackulak, and A. Dueck, "Reducing the risk of requirements volatility : findings from an empirical survey," *J. Softw. Maint. Evol. Res. Pract.*, vol. 23(5), no. October 2010, pp. 375–393, 2011.

[17]   M. Giffin, O. de Weck, G. Bounova, R. Keller, C. Eckert, and P. J. Clarkson, "Change Propagation Analysis in Complex Technical Systems," *J. Mech. Des.*, vol. 131, no. 8, p. 081001, 2009.

[18]   B. Morkos, P. Shankar, and J. D. Summers, "Predicting requirement change propagation, using higher order design structure matrices: an industry case study," *J. Eng. Des.*, vol. 23, no. 12, pp. 905–926, Dec. 2012.

[19]   S. Ferreira, J. Collofello, D. Shunk, and G. Mackulak, "Understanding the Effects of Requirements Volatility in Software Engineering by Using Analytical Modeling and Software Process Simulation," *J. Syst. Softw.*, vol. 82, no. 10, pp. 1568–1577, Oct. 2009.

[20]   E. C. Y. Koh, N. H. M. Caldwell, and P. J. Clarkson, "A Method to Assess the Effects of Engineering Change Propagation," *Res. Eng. Des.*, vol. 23, no. 4, pp. 329–351, Mar. 2012.

[21]   K. T. Ulrich and S. D. Eppinger, *Product Design and Development*. New York, McGraw-Hill, Inc., 2000.

[22]   A. Häggman, T. Honda, and M. Yang, "The Influence of Timing in Exploratory Prototyping and Other Activities in Design Projects," in *ASME International Design Engineering Technical Conferences*, 2013.