Design Requirements Formulation: A Framework and Analysis

by

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Abstract

This thesis focuses on the early stages of the product development process, during which the set of design requirements is formulated. Given the proven importance of a comprehensive set of design requirements in the market acceptance of a product, we explore the formulation of design requirements and the potential sources of uncertainty that can arise during this early phase of the development process. This thesis seeks to answer two main questions: What events and conditions are likely to increase the project's uncertainty during the formulation of the design requirements? And, in what way can the effects of these events and conditions be avoided or mitigated? Using the information gathered through an extensive literature review, a descriptive framework was compiled. The information used was validated following two different paths: first, the evolution of the set of design requirements of several teams in a product design and development class was analyzed and, second, veterans of industry were interviewed about their experiences during the development process.

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Chapter 1

Introduction

"You can't just ask customers what they want and then try to give that to them. By the time you get it built, they'll want something new" - *Steve Jobs*

It is clear that corporations can benefit enormously from research in product design. After all, better products generally sell more. It is also true that by streamlining their development processes and mitigating the sources of uncertainty that plague the development environment they can increase their profit margins and improve their performance; however, the competitive nature of the free market gives to this type of research a far more important benefit. Firms with better processes perform financially better than their less sophisticated counterparts, but by expanding the knowledge of the field and making it readily available, researchers can help enhance competitiveness and diminish industry-wide waste of resources; outcomes that are substantially beneficial to the well-being of society.

This thesis focuses on the very beginning of the product development process (PDP); the phase during which the stakeholders' needs are collected and translated into information that the engineers can use to develop a better product. Its main objective is to explore the formulation of design requirements and the associated uncertainties that can affect the process to find what factors are likely to increase the volatility, or the likelihood of change of the design requirements, in order to create a platform from which uncertainty prevention and mitigation measures could be built

upon.

Recently, there has been an increase in new research concerning the design and development of consumer products, as evidenced by the large number of papers published in the last five years. Behind this wave there is an industry-wide hunger to improve the output rate of successful products; however, despite the vast available literature, the understanding of the connection between a successfully designed product and a commercially successful one remains vague. There is always a certain degree of different uncertainties that can impact the outcome of any product development process and makes charting the commercial performance of a product a very difficult task; but, by identifying and understanding the effects of certain adverse events and conditions it is possible to avert costly changes of direction and possibly commercial failure.

Before delving into the intricacies of these events and conditions, which we will refer henceforth as sources of uncertainty, it is important to note that the development of a product is not carried out by a single individual and it does not happen in a vacuum. Generally, a product is developed by a design team; a group of skilled individuals with different backgrounds and personalities. The team, while being at the very core of the development process, is dependent on the actions of the organization from within it operates, which, in a similar manner is dependent on the circumstances of the industry and the market that are, finally, subjected to the cultural, political, and social trends of society. This, often dysfunctional, web of connections and hierarchies makes it hard for researchers to pinpoint the root causes behind many of the eventualities that can delay, redirect, or halt the PDP.

At the center of a successful PDP there is a simple canon: Customers generally buy the products that better satisfy their needs. There might be other reasons for a poor commercial performance, but they are all directly or indirectly connected to this one rule. It is the responsibility of the design team to discover these needs and develop the appropriate solutions, and it is the responsibility of the team leader and management to support this effort by ensuring the timely delivery of results and the proper allocation of resources. Time of development has a substantial impact on the

outcome of the PDP [1]. According to the literature, there are measurable financial consequences to delaying the launch of a product. Still, financial performance is not the only measurement of success. Griffin et al. explore the different sides of the PDP and compile a list of measurements that we will use to benchmark success from the perspective of the different stakeholders and to understand the relative importance of the project's goals [2].

The information - including user needs, product characteristics, and performance values - is stored in compact form in a document referred throughout this thesis as a *product contract.* Design requirements are the way the in which the needs of the customers are transmitted to the engineering team in a way they can act upon them. Clear and stable design requirements are a key element of a successful PDP. The literature corroborates this in a brand new study which has shown that during the formulation of design requirements, adverse events can be particularly disrupting and hard to mitigate [3]. As the team evaluates their results and new feedback is received, it is expected for the design requirements to evolve; however, *unforeseen* changes to the product contract can be costly to the firm, not only because of the inherent price of propagating them throughout the downstream phases of the process, but also due to the delays that they might cause.

Preventing, or at least forecasting, those changes can reduce the uncertainty of the PDP substantially, and understanding the reasons behind them and their potential consequences are a necessary first step to the reduction of wasted resources. Beyond the internal works of the design team, there are a number of external events that can derail the PDP by impacting the product contract and forcing changes to the design requirements. These events are varied and the literature goes to painstaking lengths to identify their origins. Since this research is written from the perspective of the design team the sources of uncertainty have been additionally categorized by the elements of the product contract that they can affect.

After carrying out an extensive literature review, we also carried out a quantitative and qualitative analysis of the evolution of product contracts as they were developed by several teams of experienced engineers in an academic setting. Additionally, in-

terviews with industry experts were used to corroborate the conclusions and set the basis for future work. At the end of this thesis, all the valuable information was condensed in a clear and intuitive graphic framework to be used as a guide for future research.

This thesis aims to answer two research questions:

1. What events and conditions are likely to increase the project's uncertainty during the formulation of the design requirements?

2. In what way can the effects of these events and conditions be avoided or mitigated?

Chapter 2

Literature Review

2.1 Definitions of Success and Failure

"Failure is success if we learn from it" - *Michael Forbes*

The difference between success and failure in the outcome of a product's development is a topic of great importance not only to academia but also, understandably, to industry. Firms invest extraordinary sums of capital trying to achieve success, which is really not surprising considering that their own status in the industry, not to mention profits, are with a small degree of independence almost always tied to the success of their products in the market. Granted, some firms, despite having embarrassing failures in their product history are still considered successful companies. Such firms have been able to upset failure with an equally or better number of successful products. After all, it is unlikely that we would consider the makers of New Coke, the Edsel, or the Betamax successful companies without thinking about Classic Coke, the Mustang, and the PlayStation.

The three companies responsible for those dismal failures and great successes are, of course, Coca-Cola, Ford, and Sony; three firms that despite having their shares of disappointing flops have, at least in the consumers minds, become enduring models of business acumen. Thanks to some of the most successful products in history, their brands are recognizable around the world. As consumers we can almost feel

when a new product has become a success. We buy it, our friends buy it, we see it everywhere - on TV, on films, on billboards - and after a while it inserts itself into the fabric of our daily lives; however, these are only symptoms of success, not the essence of it. The launch of a product can have a large gamma of outcomes, and although the rhetoric from those invested in its performance might skew its meaning with meaningless superlatives, the difference between an incredibly successful product and a marginally successful might provide subtle but relevant hints on the causes of success.

Several key measurements in the literature can be used to understand and quantify the degree of success or failure of a given product. Some of these measurements are taken from the business literature, while others come from the engineering field. By combining them into a single interpretation we expected to obtain a more complete representation of the development environment. Griffin et al. organized the possible measures of success in five categories: "customer measures, financial measures, process measures, firm-level measures, and program measures" [2]. Each of the categories encompasses a sphere of thought and looks at the results of the product development from the eyes of a different stakeholder.

The customer measures are related to the perception of the consumer towards the product. Namely, things like "market share [and] customer satisfaction" [2] fall within this subset. Despite not really having an explicit impact on the company's bottom line, they are the most direct and enduring measurements of success because of the ripples they create in the consumer disposition, not only towards the product itself, but also towards the brand and the company behind it [4]. They are, thus, the most valuable achievements that can be obtained from a project. The lasting benefits that can be harvested by pursuing excellence under these parameters are evident in the auto industry. For years, Toyota was known for its reliable and affordable cars, especially when compared with its American counter-parts. One of its principles as described by impartial observers was to "base [their] management decisions on a long-term philosophy, even at the expense of short-term goals" [5]. This perception gave its consumers an extra incentive to buy their cars, creating a sort of positive

feedback which has allowed Toyota to become one of the largest and most successful car manufacturers in the world.

The financial measures, on the other hand, provide a much more direct way of assessing the results of the development process. Profits and margins are clear and quantifiable [2]. They can be used to satisfy investors and monitor the present conditions of the firm; however, they can change quickly and although they might bear some connection to the quality of a given product, they don't necessarily do so at all times. Kaul et al. succinctly list the introduction of a new product together with product modifications and abandonment as the derivatives of a company's "quest to improve or attain its profit objectives" [6]; however, it would be a mistake in the long run for a firm to aim solely on succeeding under these short-term parameters at the expenses of the long term goals. Firms that do so are in danger of losing their standing in the industry and as a consequence losing future profits. One classic example of the effects of this *penny pinching* attitude comes once again from the auto-industry. The Ford Pinto, manufactured from 1971 to 1976, became infamous when it was discovered that the company had decided against better protecting the fuel tank to avoid the danger of it bursting during rear-end collisions. Fixing the problem would have cost the company only an extra "$11 per Pinto". In 1978 Ford was not only forced to recall "1.4 million Pintos and its cousin the Mercury Bobcat" and pay millions in claims, but the botched strategy also cost the company the esteem, and thus the money, of many of its former customers [7].

The process measures can, at first, seem quite irrelevant if the product fail to succeed in the two previously discussed categories; yet, there is evidence connecting things like "technical performance [and] on-time delivery" [2] to the traditionally understood definition of success. They are effects more than consequences, causes more than symptoms. And they are intrinsically dependent on the actions and behavior of the design team, the core entity on the development process of a product. It is important, nevertheless, to remark that by itself, a thing like technical performance does not guarantee success. The much hyped Segway PT is a prime example of a product showcasing breakthrough technology that failed to find its place in the mar-

ket. Marketed as the means of transportation of the future, the Segway failed to reach the masses as it was intended. Its price put it beyond the means of most families, and despite its clever design and advance technology, it was relegated to a small number of niche markets [8].

Firm-level measures are aggregates of single product outcomes. They define the long-term standing of the company within the industry, and provide an idea of its historical and future trajectory. Parameters like "success/ failure rates [and] percentages of sales consisting on new products" [2] are measures that can only be affected through careful planning and a thoughtful business strategy. The new wave of Apple products that started with the launch of the iPod in 2001 is a great, and much studied, example of an overall strategy to position the company as the leader in many different markets through the symbiotic relation among several seemingly independent products.

And finally, program measures are a specific and sometime artificial set of objectives that firms define themselves. Many times they reflect the idiosyncrasy of the organization and despite not being, in many occasions, helpful towards the finances of the company, they can serve as sources of good publicity, and should not be underestimated. An example of this could be the Bugatti Veyron. Despite costing the Volkswagen Group millions of dollars in research and development, it was an engineering masterpiece, the fastest car in the world, and a fantastic source of good publicity for the company and its brands [9].

Depending on the perspective of the stakeholders, any one of the parameters classified into these categories can be used to define a product as a success; but there are sensible combinations that can be quite convincing not only to the shareholders and consumers, but also to the upper management of the organization. Meeting the desired parameters is critical for the survival of any firm, but if it were a matter of investing enough money or time in the development of a product, there would rarely be any unexpected failures. The truth is that achieving the prescribed goals to qualify a product as a success is made difficult by the number and interdependency of the factors involved. In later sections, we will delve deeper into these elements and the

ways a firm can react to them, but for now we'll just touch on the elements of the market that as a whole comprise the environment in which a product must perform.

A product is not born in a vacuum. Even brand new ideas propelled by brand new technologies are developed in the midst of a turbulent environment. For many firms, this reality makes the process of creating and launching new products very unpredictable. It is common for executives to see change as a threat and, generally, this fear can increase the vulnerability of their position. It is hard to blame them though, considering the multitude of things that require consideration. Hultnik et al. describe some of the most important variables that could affect a firm's strategy. This is not in any way an exhaustive list, but it does a good job of taking into account the different facets of modern businesses [10].

The nature of the product itself is critical, of course. Factors like "product innovativeness, product development cycle time, and product newness" can be advantages or serious disadvantages to a firm. What makes a product special should not only be part of the advertisement plan, but it should also be the objective of any self-respected design team. Given that even a thoroughly designed product can fail if the sales and marketing efforts are aimed at the wrong crowd, other elements, such as "branding and targeting strategy" also need to be well defined. Moreover, there are factors completely independent of the product itself that add up to the high degree of complexity, such as: "market growth rate, number of competitors, distribution channels, pricing policy, and sales force intensity" [10].

By looking at these murky waters, it is easy to see why the industry has not been able to demystify what makes a successful product a success. There are of course firms with a better than average history of success, but even the best of them still suffer from the occasional time-consuming and cost-intensive failure. At the end, the reality is that even by doing everything right a firm cannot ensure that their new product will be successful, but they can - by strengthening their development process, understanding the internal and external sources of uncertainty involved, and adapting to change - substantially reduce the chances of failure [11].

2.2 The Importance of Good Design Requirements

"Lost time is never found again" - *Benjamin Franklin*

The true essence of product design is to observe and understand. We will describe many forms of sources of uncertainty that can hamper the development of a product by increasing the related uncertainty, but the reality is that without a compelling reason to exist a product is doomed to failure despite the quality of the process, the experience of the engineers, or the skill level of the managers. Understanding the wants and needs of the different stakeholders of the product's life is the most important job of a product designer [12]. As the primary stakeholder, the user should hold a privileged position during the development process; still he rarely is the only one [13]. Other important stakeholders can include the firm itself, the government as representative of the general public, the distributors, and the disposing firms. Some of these entities can have inherently opposed requirements and it is the job of the team to balance and prioritize each one.

Simply put "the commercial success of a new product depends on how well the product's design meets [the stakeholders'] needs." [14] The process of capturing and monitoring the stakeholders' needs starts at the very beginning of the design process and it lasts for almost the entire process. It involves identifying who the actual stakeholders are and discovering, not what they want, but what they need. This is a crucial step of the process given that once compiled, this set of needs will become the blueprint for the finished product. From observing and understanding the user needs, through a series of stages that we will described in the following sections, a set of design requirements - each with a need, a measurable attribute, and a range of target values - can be formulated [15]. The design team must be very careful during these early stages of design, because in the same way that a building will crumble when built using faulty plans, a product will fail when based on an incomplete, wrong, and/or unfeasible set of design requirements.

In his 1995 paper, Bloch provides an insightful metaphor to understand the true nature of design and development. He sees the definition of design requirements as

the creation of a boundary that once set is filled by the characteristics of the final product. If the boundaries are sound, and the final product fits properly within them, then the design team can claim to have been successful at understanding the essence of the stakeholders' needs. Bloch labels these constraints: "performance, ergonomics, production and cost, regulatory and legal, marketing, and designer's" depending on the type of design requirements and the stakeholder that each one addresses [16][17].

The performance requirements prescribe the way a product will work. It is the job of the design team to ensure the functional performance of the final product [18]. If the product is not capable of performing at the level prescribed by the formulated set of design requirements or if the target values of the design requirements do not satisfy the user's expectations [19], it makes it less likely to be a success. The ergonomic requirements describe the way the users are supposed to interact with the product. And likewise the project will be likely considered a failure, if the design team cannot envision the product in a way that it is visually appealing and relatively intuitive to use with the skill sets of the target customers [20]. On the other hand, the marketing requirement refers to the way a product must be designed to be easily handled, transported, stored, and disposed of at the end of its useful life. The production and cost requirements refer to the way the product is developed and manufactured. The design team, supervised by management, must ensure that the cost of the project fits within the overall financial strategy of the firm. The legal and regulatory requirements prescribe the standards imposed upon the industry by the overseeing regulatory agencies and to the patents that the product design must adhere to. Finally, the designer's requirements can be used to describe the designers' personal goals [16].

Most PDPs suffer from problematic situations every so often, and some of the problems can be easily dealt with; however, the effects of change on a product's development due to the discovery of issues within the set of design requirements can be very traumatic to carry out. They may not be by themselves expensive or time-consuming, but they can be substantially worsen by the propagation and accumulation of the modifications they can trigger [21]. Engineers and designers base

many of the decisions they make during the ideation phase on the design requirements conceived in the previous stages of development, so it is not surprising to see that, according to new research, forced changes require the largest investment on the part of the firm due to the incurred mitigation costs [3]. The detection of problematic issues within the set of design requirements is already an inherent part of the design process. Increasing the stability of the requirements and improving the reaction techniques represent valuable areas of expansion and would provide useful tools to decrease the uncertainty of the project.

Beyond the direct costs inflicted on the firm by the work that must be redone due to changes in the set of requirements of a product, the underlying costs of potential delays should also be taken into account. They are not only responsible for monetary losses but they can also damage the firm's reputation. In fact, according to Hendricks, "the evidence suggests that there are significant penalties for not introducing new products on time. On average, delay announcements decrease the market value of the firm by 5.25%" [1]. This reality sometimes forces firms to impose unrealistic time frames, but since the pressure to fulfill the production deadlines can have a tremendously detrimental effect on the effectiveness of the design team it is critical for the company to find a balance between effectiveness and promptness.

2.3 Risky Business

"Failure is not fatal, but failure to change might be" - *John Wooden*

We have so far listed some of the events and conditions that can increase the uncertainty of developing a new product. They are, when considered as a whole, intimidating. They can arise from all sides of the business and each one separately can have a tremendous negative impact on the development process; still, there is order and even degrees of importance in this seemingly chaotic environment. A risky event, as defined by Segismundo et al. is "an undesirable event that can cause delays, excessive expenses, and unsatisfactory results for the project, the organization, society, [and] the environment" [22]. This definition is very broad, so Segismundo

came up with a way of categorizing these events depending on their origin. This method allows us to establish some kind of spheres of influence. Understanding the sources of uncertainty can help those in the right positions to confront them by developing effective prevention and mitigation strategies . Given the focus of this research on the design team and the effects of their actions on the outcome of the development process we will considered the sources of uncertainty from the perspective of the engineers and designers that compose it. Segismundo splits the events in four categories: technical, managerial, organizational, and peripheral [22].

The reaction to the "technical sources of uncertainty [that] stem from the use of unproven or complex technology, unrealistic performance requirements, and changes in the technology used" [22] is the responsibility of the research and engineering teams. As the pushers of innovation they must, at all times, remain aware of the technological advances in their respective fields. They must also focus their efforts on finding new ways of implementing the technology in ways that help the firm better address its customers' needs. The truth is technology changes continuously, and this makes it very hard to keep up. Timing is essential and staying one step ahead of technological obsolescence can be a powerful advantage in the market.

"The category of managerial sources of uncertainty to the project is characterized by the issues caused by the inadequate allocation of resources, unrealistic estimates and poor quality of the project plan" [22]. Managers are simultaneously leaders and followers. They must act as a bridge between the goals of the organization and those of the design and engineering teams that depend on their leadership. Like hired ship captains, they must know how to follow an itinerary, command the crew, and keep the owners happy. It is not an easy task. Among other things, sometimes different interests put managers in the difficult position of taking sides. This can make decrease their influence and there value to the firm. Good managers, however, know that in order to protect the creative minds that benefit the firm, they must shield the design team from unwanted interference, while at the same time holding the reins to avoid unnecessary costs and delays [23].

Organizational sources of uncertainty are caused by incoherent project goals, a lack of project prioritization, and insufficient or interrupted financing. [22] Unlike clocks, firms are rarely allowed a unique purpose. Within each company, many elements work in parallel, but not always in harmony to accomplish the goals of the organization. This can result in enormous waste of resources, time, and energy. For the design team the lack of defined objectives and clear directives is quite negative. Many times engineers and designers will be unwilling to invest the time in a specific direction when they feel there is no confidence in it from those who actually lead the firm. It is the job of the organization's leaders to back the team by adopting transparent processes and better support systems.

Lastly, "peripheral sources of uncertainty are those caused by the legislation, market trends, labor issues, and changes in the priorities of the project sponsor" [22]. They are clearly beyond the control of the organization and can cause many problems for the company, especially when they occur unexpectedly; however, they generally do not occur fast enough to arise without some type of warning. Firms often take into account the probability of these events occurring into their short and medium range strategies; however, when they fail to do it, the consequences are historically devastating.

These categorization is a very useful way of studying the conditions under which a product is designed, but they don't encompass all the possible sources of uncertainty. In his work, Segismundo seems to delineate only the events that come from the outside of the design team. For the purpose of these research we'll follow Segismundo's steps but with a slight modification. We will trace a line around the design team, a boundary separating it from the sources of uncertainty that affect the process, but over which the members don't have any direct control. The design team, as the main driving force behind the PDP, cannot be treated as a black box. Certain dynamics within it can have a huge negative impact to the development of a product and deserve to be explained. For this reason we will use a simplified but extended categorization method where all the events and conditions are considered either internal or external, with the latter being comprised by the four types mentioned by Segismundo, and the

former being related to the characteristics and behavior of the design team itself.

2.3.1 Internal Sources of Uncertainty

Design Team Orientation

It is particularly important for the members of the design team, and the team as a whole to have the correct goals aligned with the product they are tasked with creating. Many times design teams can fall in the trap of asking the wrong questions or skipping critical stages. Be it through a mismanagement of the team's skill set or an overemphasis on the importance of the resources allocated to the project over the actual project goals, teams can lose sight of what is actually important: correctly fulfilling the stakeholders' needs. In his 1997 work, Burchill et al. describe two scenarios: one where the team is time-oriented and another where it is market-oriented, which to better adhere to the vocabulary of this research we will designate henceforth as resources-oriented and stakeholder-oriented [24].

According to Burchill, a resources-oriented team "attempts to specify the design objectives in an accelerated period of time." While a market-oriented team attempts "to develop credible design objectives reflecting a deep appreciation of the customers' requirements". In more general terms, one team suffers under the constraint of limited resources and lacks the discipline to tackle the perennial problem of capturing what their product is supposed to be. Clearly, "limited resources" is the name of the game in product design. No firm, no matter how big or successful, likes to write blank checks to their design teams, so knowing how to work under pressure is not only preferred, but necessary. Similar projects are likely to be under similar outside pressures to fit into a given time-frame or budget [24].

Despite similar conditions, the consequences of the different orientations are, not only marked, but also worrisome. According to Burchill, a resources-oriented team will "lack commitment to the product concept" and will have to deal with the "expectation that the final product [will] differ from the initial concept". While a stakeholder-oriented team will "display commitment to the product concept and can

credibly trace their decision process when asked to justify their choices" [24]. The time that each sub-stage of the development process will take should not be underestimated, a mistake that can be historically traced as the cause behind many failed products. Good planning, awareness, and flexibility are, evidently, skills that can help a team maintain a proper orientation. All of which can be nourished through the development of a process rigid enough to facilitate the fulfillment of deadlines, but adaptable enough to provide the freedom necessary for the team members to transit each of the development stages in a fluid and time-appropriate manner.

Design Team Dynamic

"Collaboration enhances the product's design along with improving the execution of the development process." [14] It is very common for a team to be composed by people with different functional backgrounds and experience levels; and since the composition of the team itself plays an important part in the formulation of design requirements [25], it is crucial to understand the way the creativity and effectiveness of the team as a whole depends on the sum of its individual parts. Furthermore, it is also relevant to explore the way the interaction between the design team and the rest of the organization - primary composed by sales/marketing, manufacturing engineering, and production [14] - takes place, given that "the more the external communication, the higher the managerial ratings of innovation" [26].

The literature delves into the specific effects of functional and tenure diversity. With a high functional diversity, "the team is more likely [to] communicate outside the team's boundaries. This communication [takes place with] groups such as marketing, manufacturing, and top management" [26]; while "tenure diversity impacts [the] internal group dynamics rather than [the] external communications. Tenure diversity is associated with improved task work such as clarifying group goals and setting priorities. In turn, this clarity is associated with high team ratings of overall performance" [26].

It would be easy to assume that a more functionally diverse team has an advantage when designing a product. After all it is easy to think that with a broader set of skills,

a team has more tools to understand and solve the problem at hand; "Yet diversity is not solely positive. While it does produce internal processes and external communications that facilitate performance, it also directly impedes performance. Overall the effect of diversity on performance is negative, even though some aspects of group work are enhanced. It may be that for these teams diversity brings more creativity to problem solving and product development, but it impedes implementation because there is less capability for teamwork than there is for homogeneous teams" [27].

Ancona suggests that to counter these detrimental effects, "the team must find a way to garner the positive process effects of diversity. At the team level, greater negotiation and conflict resolution skills may be necessary. At the organization level, the team may need to be protected from external political pressures and rewarded for team, rather than functional, outcomes." This is why improving the flow of knowledge through the organizational boundaries and finding methods of sharing the institutional memory become valuable skills [26]. After all, there is substantial evidence in the literature showing how the product development process "greatly [benefits] from knowledge management as the activities that consist of it have an essential creative character and, therefore, depend basically on the knowledge and abilities of people that perform them" [27].

Beyond having different skills and experience-levels or perhaps because of this, "product innovators often do not collaborate across departments" [14]. This disrupts the flow of knowledge and prevents the organizational memory to be used at its full potential. It is known that "higher organizational memory levels enhance the short-term financial performance of new products whereas greater memory dispersion increases both the performance and creativity of new products" [28]. But this jamming of the communications causes a gap in the shared knowledge that can have "a negative and significant effect on the economic performance of the Company" [29].

The disruption of communication can be caused by the incompatible characteristics of the different departments "each focusing on different aspects of technology-market knowledge, and making different sense of the total" [14]. It seems almost a generalization to claim that marketing, finance, and R&D people are different, but

there is evidence suggesting precisely that "inherent personality differences have been found between marketing and R&D personnel in American corporations" [2]. These people also "often differ in training and background. Marketing professionals are drawn primarily from business schools, often with a prior liberal arts background. R&D professionals are hired primarily from engineering and science schools. These differences in thought worlds suggest that marketing and R&D run the danger of developing self-contained societies in which they reside" [2]. Adding to the confusion, "marketing has and uses its own set of technological terms, [while] R&D uses different technical terms" [2]. There are also "organizational barriers [which] arise due to different task priorities and responsibilities, functional success measures unsupportive of integration, lack of top management support rewarding integration, and the perceived illegitimacy of product development" [2]. Finally, "Physical barriers frequently isolate marketing from R&D in U.S. firms" [2].

There is no easy way of changing the paradigm behind the structural order of the firm. "Knowledge boundaries are not only a critical challenge, but also a perpetual necessity because much of what organizations produce has a foundation in the specialization of different forms of knowledge" [30]. So it would be counter-productive to homogenize the firm. The members of the design team must learn to interact with each other and with the rest of the departments involve in the project. At the end, "correcting the innovation problems caused by these interpretive barriers requires cultural solutions, not only structural ones" [14].

Technical Competence

When developing a new product, the design team can be confronted with different technical scenarios. A high level of technology competency is a big part of a successful product and it is, as mentioned before, one of the advantages of having a functionally diverse design team. A product can either be based on new or existent technology, but regardless, the design team must be ready to handle the challenge of meeting the target values for the design requirements using the available technology without losing the essence of who it is that they are designing the product for [2]. Many

times engineers get caught in the excitement and difficulties of implementing a new technology and "often [fail] to link technological and market issues" [14]. This can cause a lot of issues down the pipeline given that "an effective design requires that technological possibilities for a product [be] linked with market possibilities" [14].

In fact, this issue is not only found within the design team and it is applicable to the firm as a whole. There is evidence that a technical orientation can be beneficial to the company under certain circumstances and we will go through them in a later section; however, in general focusing solely on technical competence or even prowess can have a detrimental effect. There is evidence to suggest that "when competence [is] lacking, but impetus from customers to develop [technological] competence [is] sufficiently strong, established firms [can lead] successfully their industries in developing the competencies required for sustaining technological change, [but] when technological competence [exists], but impetus from customers [is] lacking, firms [are] unable to commercialize what they already could do. This is because disruptive technologies initially tend to be saleable only in different markets whose economic and financial characteristics render them unattractive to established firms" [31].

2.3.2 External Sources of Uncertainty

As we have mentioned before, there is significant interaction between the design team and the external world. The engineers must deal with a continuous flow of inwards and outwards information. "New products are demanded and developed with attributes to attend specific segments of the market, to incorporate diverse technologies, to be integrated into other products and uses, and to adjust them to new standards and legal restrictions" [32] and as such, there is a multitude of factors that can steer, delay, and even stop the development process.

The firm and, as a consequence, the design team must not only be continuously aware, but also be ready to react to the changes in the development and market environments. In *Industrial New Product Launch Strategies and Product Development Performance* Hultnik et al. give a comprehensive list of many of these variable factors, which include: "product Innovativeness, NPD cycle time, product newness, market

growth rate, stage at the PLC, targeting strategy, number of competitors, product advantage, driver of NPD, innovation strategy, product branding decisions, breadth of assortment, distribution channels, distribution expenditures and intensity, pricing level and policy, expenditures, sales force intensity" [10]. The firm's ability to react and adapt its efforts has been and will continue to be a recurrent topic of discussion in this paper. Many of the variable factors can be studied and monitored during the pre-planning stage of the product development, but because of their variable nature, the design team in conjunction with management must be ready to react to the changes throughout the entire process. When these and other factors tend to change rapidly, the development environment can be referred to as turbulent. In this type of environments "several factors lead to high product development performance [and] they are substantially different from those factors identified in studies based in more traditional environments" [33].

Iansiti, in his 1995 paper *Shooting the Rapids: Managing Product Development in Turbulent Environments* describes the traditional models for product development as focused on avoiding unnecessary change as a way of diminishing uncertainty. He goes on to describe mature industries such as the automobile or appliance industries as cautious examples of business models. "They emphasize the need for avoiding unnecessary change and uncertainty in the evolution of technology and market needs. Their focus is on developing a structured process with clearly defined and sequential phases, through which the future product is defined, designed, transferred to the manufacturing plant, and rolled out to the market" [33]. The way these mature industries measure performance "is related to mechanisms that add clarity and stability to the project, such as a clear project definition phase as well as a stable product concept and specification. The emphasis is on a process aimed at achieving focused and efficient project execution, involving strong project leadership, integrated problem solving, and team-based organizational structures" [33]. These industries are known for very iterative product lines and thrive in the slow but less risky evolution of their products through the implementation of reliable and mature technologies.

On the other hand, successful firms in highly turbulent industries were described

by Iansiti as embracers of change. "They have the ability to gather and rapidly respond to new knowledge about technical and market information as a project evolves. Their flexible approach is not simply a function of hiring creative individuals or of implementing an organic organizational structure. Instead, significant systemic changes in a project's definition and basic direction are managed pro-actively by creating a development process and a product architecture that increase the speed by which the organization can react to such changes" [33].

The second type of firm is clearly prepared for the newer, more dynamic markets that seem to be becoming the rule rather than the exception in today's economic panorama; however, maintaining the rhythm necessary to react to the potentially variable sources of uncertainty requires a considerable effort. It is our believe that by following certain primordial stages to formulate a thorough set of design requirement and by enhancing the awareness of the design team to the potential changes and their respective consequences, the uncertainty of a highly turbulent development environment can be mitigated and the detrimental effects of the changes successfully mitigated.

Firm Strategy

We talked before about the orientation that a design team must keep throughout the development process in order to reduce the risk of losing its focus on fulfilling the stakeholders' needs; however, we haven't discussed the role of the firm as a whole in establishing an appropriate stance to the design of a given product. It is a fact that depending on the nature of the product and the target market firms must calibrate their efforts and the allocation of capital in different ways. A firm can either have a competitive, technology, or consumer orientation [34].

A firm with a competitive orientation is well suited for mature markets with a lot of competition. The competitive stance allows the company "to develop innovations with lower costs, a critical element of success" [34]. It also permits the company to increase its market share by undermining its competitors' positions. The main issue with this stance is that it relies too much on the financial muscle of the company and

it could potentially harm its wellbeing if the demand fails to reach the expected level.

A technology-oriented firm is, on the other hand, well suited for new and uncertain markets where consumers need a way of differentiating the new products from their competitors. The goal of this orientation is to position the firm at the Avant-guard of technology in the consumer's mind. There are; however, certain disadvantages to this stance. First, a technology-oriented firm needs to bear the bulk cost of the innovation. In addition, it might overstate the importance of new technologies and end up designing a product based on what they are capable of doing instead on what the users need.

Finally, a consumer-oriented gains customers by focusing on satisfying the needs of the product's stakeholders. However, becoming a highly empathic company is not easy, and it requires the organization to enhance the cohesion of its different departments and ensemble a highly experienced, flexible, and discipline design team. The perfect combination is, therefore, a highly empathic, but also technologically competent firm. "These orientations together lead to products which perform better and the firm will be able to market innovations better, thereby achieving a superior level of performance" [34].

Management's Priorities

There is a continuous flow of information and directives between the design team and the rest of the company; after all, is at the management level where most of the important decisions are taken throughout the PDP. It is important for the team to comply with the boundaries, rhythm, and deadlines impose by executives of the firm, since as specialist in their respective areas engineers and designers are not generally in a position to understand the overall medium and long term plans of the company; however, sometimes the interference of the managers on the creative process that take places within the design team can be disruptive and dampen innovation.

Design teams and their leaders must deal on occasions with "inadequate allocation of resources, unrealistic estimates and poor quality of the project plan" [22] and there is not much they can do to avoid these issues. It is critical for managers to iden-

tify when their actions are having a detrimental effect in the design output of their teams. They must understand that their most valuable "resources [are] the product and process engineers and technicians who dedicated their time to product development" [35] and that since "many organizations must manage concurrent projects that place competing demands on shared human and technical resources" [35], it is also important to maintain a clear and flexible process while building good roads of communication between the different departments in the firm.

Competitors' Strategies

Beyond designing a product capable of fulfilling the needs and wants of its potential users, the design team must also constantly monitor, behave, and react to the actions of their firm's competitors. The reality is that there are many ways of solving a given problem, but not all of them are ideal. Certain technologies are better - or at least are perceived as better - by the general public and, as such, the product that implements them has usually an advantage in the market. In addition, the way a product looks and feels in comparison to its direct competition is, despite being more subjective, an important contributor to the commercial performance of a product [36]. It is not an easy task to adapt to the movements of the competitor's product development, and in most cases it involves an organization level stratagem.

Depending on the industry, the responses can have different frequency rates and impact on the product. In young and dynamic industries competitive response can occur habitually, since the customers are willing to trade one product for another because of the slightest edge in design. In other, more mature sectors, the competition responses are more predictable since the inertia of the system is too great to allow for large impactful events to occur at a high rate, and the historical trajectory of each firm and their products' perceived quality bears a lot of weight in the customers' minds. The design team is the spearhead for the rest of the company when it is facing the changes to the conditions in the market.

Technology

A very similar situation can occur when the available technology changes. This is a common occurrence in the newer industries such as the software and computer hardware sectors, but in certain occasions it can also happen in the more traditional industries such as the automobile sector. Many times the advances in technology are not driven by the powerful large corporations, although this is sometimes the case. In fact, many of the technologies currently being commercialized were originally researched and developed by universities, individuals, and small startups, and as such they can take the current players in the market by surprise.

However, it is important not to confuse a newer technology with a better solution [36]. The key to transferring the benefits of scientific research into the successful commercialization of a product lies in the smart implementation of the new technology. This means using the appropriate technology to satisfy the needs of the users in the best way possible. Sometimes, as mentioned before, the true goals of a product's development can get distorted by the rise of brand new technologies in the market. The engineering team's temptation to use technology as a way of patching of the shortcomings of the pre-planning and exploration stages of a product's development should not be understated because the technology could not only be costly to implement, but could also give the company a false sense of confidence that can be harmful when calculating the expected profits from the endeavor.

Government's Regulations

Generally, big firms have representatives in the halls of government, and with good reason. There are very few other ways in which the development of a product can be stopped on its tracks with such definitive intent [37]. Government regulations can take months to write and years to be enacted into law, but once that happen they can become an unavoidable obstacle. They cannot be mitigated, and the design team can either work around them or scrap the project altogether. Information is the only real defense against this type of uncertainty. The firm must make sure to understand the

political currents and social trends that will constraint the market in the near future. Their financial performance depends on it. Given that safety and environmental standards are the most common types of regulations that can affect a product, another way of ensuring the least amount of disruption is through self-regulation. Although it sometimes can represent a meaningful investment it not only provides breathing room in case governments see fit to intervene, but it also provides the added bonus of goodwill and free publicity with the people and interested groups. Additionally, firms are encouraged to work with the government, helping the representatives to better understand the industry in order to avoid the implementation of costly and unreachable standards.

Legal Status

Rarely a firm owns all the technology used in its products and generally these companies must lease the rights to use those technologies from other entities. This is a long and complicated process. Patents and their implications are a big element of the PDP [36]. Even when a company is under the believe that it owns all the technology required to develop a product, there is no way of fully knowing what third party patents they might be infringing on. This means that as the product is being designed, manufactured, and even commercialized there is a constant risk of having the entire operation stalled by pending lawsuits and other legal actions.

The design team is many times involved in the legal process, assisting the legal department. Giving the need for their technical expertise this should not come for a surprise, what comes as a surprise is that due to limited manpower; even they cannot foresee all the possible legal eventualities. That is why when designing a product and formulating its set of design requirements it is critical to leave enough leeway to allow for the modifications of certain aspects and comply with the new constraints imposed by the legal circumstances of the company.

Suppliers' Status

A similar situation occurs with suppliers. Quality, prompt delivery, and the price of parts are extremely important for the production schedule of a product [37]. When any one of those elements is not properly met, the firm can suffer from delays and unexpected expenses. Products are generally manufactured from several parts purchased in different places, sometimes in opposite locations of the globe. It is not an easy task to keep all the process running smoothly. On occasions a firm must deal with a problematic supplier, and when this happens the design team must adapt its plans to the less than ideal circumstances. This can mean changing engineering specifications, modifying a product style and ergonomics, redefining target values, and even changing materials.

Flexibility is very important in these cases, but an even greater advantage would be to use smartly implemented modularity in the design. By using commonly available parts that can be easily replaced the design team can isolate their product from the risky eventuality of losing a source rare of supplies. Of course there are issues with this approach. Some products might not be able to achieve the desired performance using commonly available parts, and the costs of designing a highly modular product might be prohibited.

Market Demand

The market could be metaphorically compared to a living organism. Like a living organism, it grows, contracts, and evolves. This behavior is expected, but the specifics can be wildly unpredictable because of the many forces involved. Seemingly superficial factors such as fashion trends and marketing collude with more transcendental ones such as technological jumps, economic booms or downturns, and even international conflicts to form a turbulent environment. Given the potential magnitude and unpredictability of these forces it is very difficult for the design team to really plan their overall strategy based on them happening; however, many firms still invest sizable resources in trying to predict the motion of the different parts, to avoid having

to change course in the middle of the design process.

These *time bombs* increase the uncertainty of the process, since they can erode the confidence of the design team on the findings of their initial exploratory research on the needs and wants of the potential customers. One way of insulating their efforts from the erratic mood changes of the market is to understand and tackle the essence of the problem that the product is trying to solve [36]. After all, the primordial elements of the customer's needs are generally the last to change with the advent of any of the previously discussed events.

Chapter 3

Framework for the Formulation of Design Requirements

There are a large number of structured methods currently being used to plan and carry out the development process of products, complex systems, and services. Many of them are industry - and even firm - specific, but the majority follow a common structure. This should not come as a surprise given that in general the actions taken by rational human beings to solve a problem are universal: observe the problem, understand its causes, design a solution, and implement it. At first, it might seem like an oversimplification, but it is just perceived that way because for us humans it is the intuitive and natural way of acting. We are wired to look at the world around us in this way in order to overcome everyday obstacles. The problem that design teams face is having to deal with all the extraneous factors, mentioned before, that can pollute the process in a way that clouds the real goals.

Kaminski [38] enumerates the general goals that any firm is required to fulfill during the development process in a way that parallels the measurements of success discussed in the previous sections. This reflection represents a solid understanding of the different inner forces that can steer the ultimate direction of the development process. Kaminski categorizes these goals under four groups: in relation to the customer he mentions their needs, and the way the product is localized, used, and regarded by them. Using the financial lens, he mentions the reduction of the development

cost, and the "profit margin along the product's life cycle"; Internally, he talks of the performance of the key elements of the product development process, and the improvement of the development tools; lastly, he also mentions the lessons that should be learn from the project, which include the reduction of launching time, the creation of rewarding options, and the innovation of development methodologies. Notice how all the goals and the different perspectives are clearly connected by the interaction of time, cost, and performance.

Any process methodology that claims to have the purpose of improving the development process must maintain these three parameters - time, cost, and performance - under constant examination. All three of these overall variables are not only dependent on the normal evolution of the product design process, but are also very susceptible to the sources of uncertainty mentioned by the literature. The framework presented in Figure 3-1 is a graphic representation of the early stages of designs under these circumstances. It reflects the real development environment, by including the most important elements: axis of time, performance and cost; the stages of development; and the internal and external sources of uncertainty.

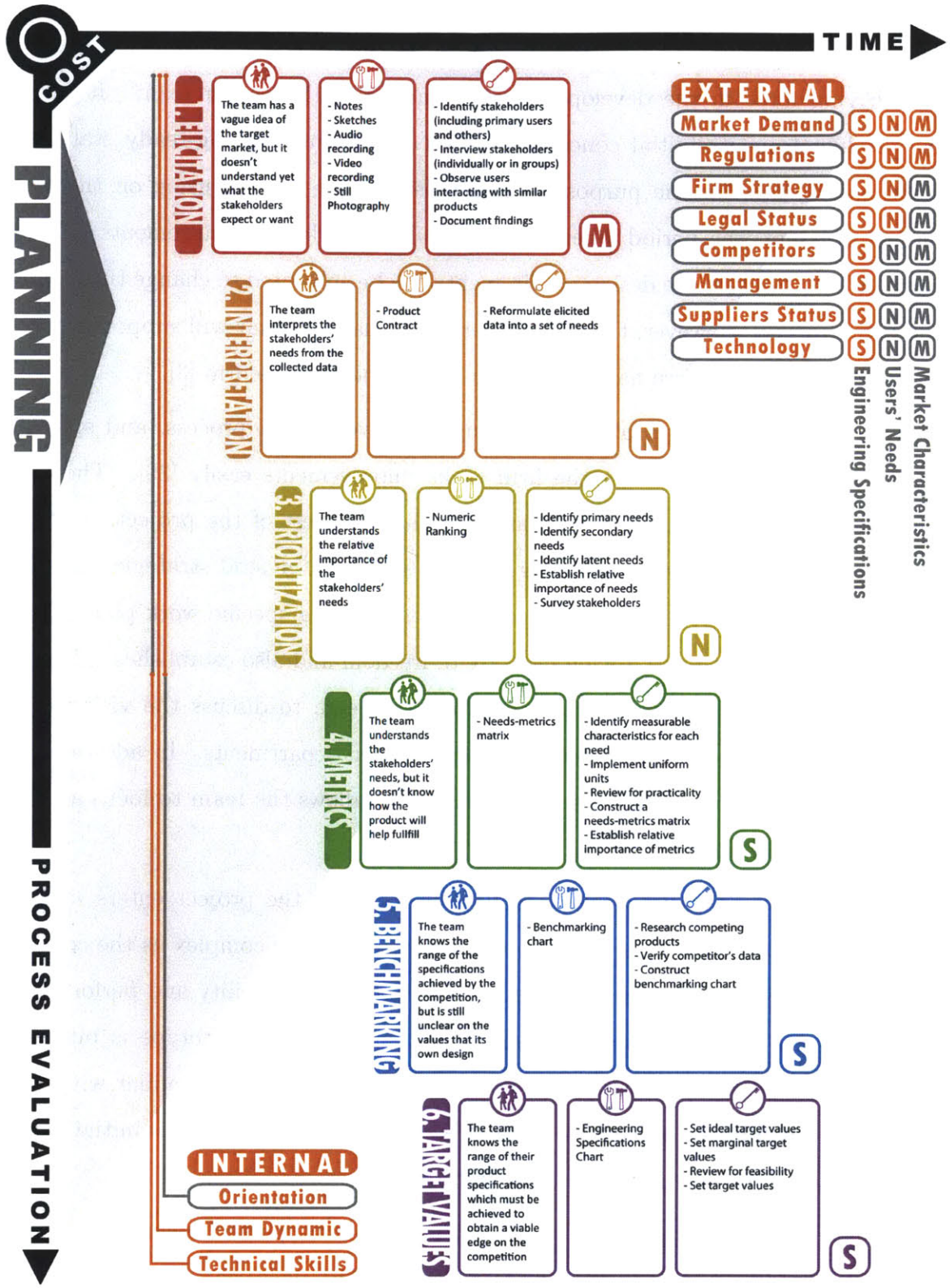

Figure 3-1: *Framework for the Formulation of Design Requirements.*

3.1 Stages

The driving force in the development environment is the design team. It carries the product from its initial conceptualization to a manufacturing-ready state. As mentioned before, for the purpose of this thesis we are only focusing on the early stages of design, the period where the original set of design requirements is being formulated. Granted, the design requirements can be subjected to change throughout the entire project; however, the original set is the platform that will support the rest of the effort and therefore has an intrinsic importance for the firm [3].

One of the advantages of standardizing the development process, and specially its early stages is that it lets the firm make improvements easily [39]. The early stages of development are more streamlined than the rest of the project. Initially, "top management starts by signaling a broad goal or a general strategic direction. It rarely hands out a clear-cut new product concept or a specific work plan. But it both offers a project team a wide measure of freedom and also establishes extremely challenging goals" [40]. This freedom allows the team to discuss the vision of its members without too much interference from other departments. In addition, the different tasks are mostly done sequentially, which allows the team to focus all their skills in a concise effort.

Once the set of design requirements is formulated, the project enters into the concept creation phase, where it becomes increasingly more complex as the concepts are tested by prototyping and other evaluation tools for feasibility and performance; however, even before the first line is sketched and the first prototype is built, the design team should have already spent considerable time getting familiar with what the product will be, or at least, to what it is supposed to achieve. This initial part of the process can be subdivided in three initial phases.

Once the overall strategy and goals of the project are passed down to the design team, the first phase of development process starts. This phase has a single discernible stage: elicitation [36]. During which, the team must understand and "develop empathy for the customer in the actual use environment of the product or service" [24].

In the subsequent phase, the soft data gathered by the members of the team needs to be organized and restructured "into a small set of well understood, carefully articulated, critical customer requirements" [24]. This is done in two stages: In the first one, the data is interpreted into needs; while in the second one, the distilled needs are prioritized [36]. Finally, during the third phase, the "key customer requirements are clearly, concisely, and unambiguously communicated in measurable terms" [24]. This is done in three stages by establishing metrics, benchmarking the competition's offerings, and defining the target values that the product will need to achieve [36].

The framework presented here goes through each of these stages. Each stage is composed by three modules: *people*, *tools*, and *key steps*. The *people* module describe the evolution of the state of the design team as an organism composed of several diverse but similarly oriented elements; the *tools* module lists the tools used in each of the stages to complete the tasks [41]; and the *key steps* module describes the tasks that must be completed at each stage to achieve the self-contained and overall goals of the project. The different stages are positioned in a way that represents their evolution with respect to time and progress towards the project's goals, with cost being represented by the third axis. Some of the stages' key tasks can overlap and this is why they are positioned, with respect to the time axis, in non-sequential structure. While, since the completion of each stage adds to the overall completion of the set of design requirements, at least in this axis they are place entirely sequentially [42].

Each stage ends with an evaluation [43]. This ensures that the pre-requisites for advancement are fulfilled in each stage before allowing the team to continue to the next one. The team can also decides after evaluating their progress to go back to any of the previous stages; however, it is worth mentioning that going back will take up resources and time, so it must be done when the investment is truly expected to pay off.

3.1.1 Elicitation

This stage represents the genesis of what will eventually become a commercial product. At this point the design team is only aware of the general direction that the company wishes to take. Firms usually develop new products to penetrate into a new market, strengthen their position by adding variety to their already available product line, or iterating and improving an existent product [32]. Be it as it may, the general strategy of the firm gives the design team hints on where to start searching for potential customers. Sometimes the elicitation is done in conjunction with the marketing departments, but at the end, it is the design team that decides which needs are worth addressing.

In addition to the users that will directly interact with the product, the design team, must also consider the rest of the entities that will have some connection to the product. These might include, but are not limited to suppliers, distributors, recycling facilities, strategic allies, and other overseers. Once all the stakeholders have been accounted for, the team can go ahead and study the way these entities interact with products that perform a similar function to the one being designed. This not only means actively interviewing people to see what their concerns are, but also passively observing them in their habitual environment when dealing with the situations in which the product is supposed to work. The tools used in this stage are varied, but they all serve to capture the behavior and experiences of the potential users in their natural environments, and the input of any additional stakeholder [44]. They include: notes, sketches, still photography, and audio and video recordings [41][36].

This stage can take up a substantial amount of time and effort. The members of the design team can bring their own experience to the table, but they should be strongly encourage to go *into the wild* to capture the needs of as many users as possible. Empathy is an extremely important attribute at this stage, and putting oneself in the place of the users is an extremely valuable exercise. It is at this stage, that teams formed by members with different backgrounds and skill sets are particularly helpful. A product can gain a substantial edge over the competition with relatively

little material resources spent. Latent needs, are also generally discovered at this stage.

3.1.2 Interpretation

At the beginning of this stage the design team is sitting on top of large quantities of recorded information provided by the marketing department and their own research. The exploratory excursions should have yielded valuable insights on the behavior of the potential users. At this point the team's main task consists in making sense of the chaotic and sometimes contradictory information gathered and distill it into a set of concise needs. The best way to do so is to generate a list known as *product contract* of what the product's design must achieve [36].

At the end of this stage the team can evaluate the broad set of goals provided by management and the marketing team. Several scenarios can occur: The set of needs might confirm the existent of a valuable opportunity to commercialize a new product; it might reflect that what management and marketing thought was a single opportunity is in fact a group of different opportunities worth pursuing with different products; it could also show the necessity to adjust the direction of the project towards a different target market; or it might contradict the project goals altogether by showing that there is no opportunity at all.

3.1.3 Prioritization

Once the set of needs is well defined, the design team must classify them and organize them in order of importance. This is done for two reasons: the first one and perhaps the most obvious one is to maintain the cost of the project under control. Users might have a substantial set of needs, but many of them might not be considered important enough to justify the increment in the cost of the project and of the final unit. And second, sometimes needs contradict each other directly - as it could be, for example, the case with volume and weight - and by prioritizing one need over the others it is possible to decide which one takes precedence at the moment of defining

the engineering specifications.

A numerical ranking method should be used. Many firms often employ "Quality Function Deployment (QFD) matrices to determine exactly what the customer wants, how the competitors meet the customer's needs, where there are opportunities niches to be filled out" [45]. The way in which the needs are organized varies from firm to firm, but generally the needs are grouped into subsets. Each subset is formed by a primary need that the product must absolutely address and a number of secondary needs that are similar in one way or another to their parent primary need. Once the groups are formed, a score system can be used to order them according to their relative importance with respect to the users and the other stakeholders. In some cases, a special distinction can be made for needs that the team feel are of particular interest to the user. These are generally considered latent needs that will provide an edge to the product over its direct competition. The list of ranked needs should be validated by surveying the different stakeholders. This is one of the most critical parts of the process, and by taking it seriously and allocating the necessary amount of time and manpower, a lot of future problems can be avoided [36].

3.1.4 Establishing Metrics

Once the set of needs has been compiled, organized, and ranked. The design team must start thinking in terms of the product's attributes that will help address each need. The exploratory phase starts giving way to the creative phase. Sometimes needs can be easily connected to the physical characteristic of a product, but that is not always the case. For example, *the product is easy to carry* can be easily connected to its weight, but it could also be achieve through a combination of many other properties such as volume, shape, and inter-phase with the user, etc.

Each of the designated measurable attributes used to satisfy the stakeholders' needs should be easily measured with a set of uniform units. In this way the team, not only simplifies its own work, but also avoids issues at the moment of transmitting the data to entities unfamiliar with the information. Afterwards, the team can use a needs-metrics matrix to organize and rank the attributes in a clear way. Sometimes

several attributes are used to address a particular need, while in other cases a single attribute can help satisfy several needs [36].

During this stage the team dynamic changes. Its members stop being receptors of information and they become designers and problem solvers. It is no wonder, then, that it is at this point when the experience and skill set of a designer starts gaining importance within the group. Product design is an iterative process, and generally the majority of the problems faced by the design team during the development of a product can be solved, at least in part by looking back at similar situations.

3.1.5 Benchmarking

Very rarely a product is born without precursors. Even when implementing brand new technology, the chances are there is a product with similar features already in the market. This could be perceived as a disadvantage, but by studying the available products, the design team can learn important lessons from their competitors' mistakes without spending large amount of capital in original research [36]. From this stage the design team can put together a comparison chart to use as reference in the next phases of development.

This is a very important step, and the information gathered here is very valuable; due to this, many times the specifications are not readily available to the public, and it is in the best interest of the company to allow its engineers to study the products to reveal the entire spectrum of the products' properties. In this way the firm can ensure that the information is accurate. The data gathered at this stage can also serve to assist the marketing department in correctly segmenting the market, which is a big component of the marketing strategy for the launch of any new product.

3.1.6 Defining Target Values

The final stage of the formulation of the set of design requirements is the definition of target values for each of the attributes that the product must have to satisfy the needs of the stakeholders. At this point the design team should have a complete

understanding of the stakeholders' situation and a solid idea of what the product performance will be. This is done by first defining the minimum or marginal values for each attribute. These numbers represent the threshold between competitive adequacy and total obsolescence, and they are generally obtained from the benchmarking stage and from the stakeholders' input. Once these are determined, the ideal values are defined. These are the values that would give the product a clear advantage over the competition, and would all but ensure a warm reception by the customers. These values must then be checked for feasibility individually and crosscheck with each other to reduce unnecessary waste of resources. It is a dangerously common mistake for firms to spend time and money in achieving a certain target value only to find out that it makes the marginal value of another attribute technically or financially impossible to achieve [46].

At this point the team dynamic must once again evolve. With a completed set of design requirements, their minds must now focus on developing a concept that fits the established parameters, without having their creativity strangled by the engineering specifications. It is likely that there is more than one path to achieve the target values and since users tend to appreciate clever solutions, it is in this moment where an open mind and *out of the box* thinking can be a huge asset for the team.

3.2 Sources of Uncertainty

The set of design requirements compiled throughout the six stages is a useful blueprint for the product's development. And by completing the key tasks described in the literature, the design team can improve the results; however, changes are not unusual. During the later stages of the process, as the team comes up with concepts and prototypes it might need to go back and modify some or all the elements of the set. In fact, even during the formulation of the requirements, problems which call for some sort of modification might arise due to the internal and external sources of uncertainty discussed in the previous sections.

In the framework, the uncertainty is shown in the background as increasing as time

passes and decreasing as the key tasks are completed and the goals of the process are achieved. Of course this is only a symbolic representation, and the uncertainty should not be seen as a linear trend, but instead as a highly sensitive variable that can be locally affected by any of the elements involved in the development process. For the purpose of the framework, the internal sources of uncertainty - team dynamic, orientation, and technical skills - are represented as areas of uncertainty that must be monitored by managers and team leaders during certain stages of the formulation of set requirements to avoid problematic situations that could lead to an incomplete or inaccurate set of design requirements.

The team dynamic can and must change throughout all the initial six stages of formulation, and as such it should be monitored in each stage to ensure the optimal combination of experience levels, functional variety, and personality types. The orientation of the team should be specially monitored during the first three stages of development, given that the successful recollection of data from the user and its subsequent organization depend greatly on the team's capacity to empathize with him. Lastly, the technical competence of the team as a unit should be specially monitored in the later three stages of the formulation of design requirements as well as during the subsequent development of concepts, given that the task of finding the optimal set of target values can be greatly facilitated by the presence of experienced engineers.

The external sources of uncertainty are, on the other hand, presented as punctual events that can - depending on their impact - send the development process back a given number of stages. Generalizing on what this number could be is really difficult because the impact depends not only on the actual event but also on the specific circumstances surrounding it; however, certain educated assumptions can be made about the effects of the events over the progress of the development process and about what elements of the set of design requirements are affected by them. There are three elements that are particularly susceptible to change: the market, which in the framework represent the actual opportunity and all the stakeholders; the needs and the relative importance of each one; and the engineering specifications, which include the attributes, and marginal and target values. Each one of these elements is

defined by the design team at a certain point of the development process.

The market's characteristics for which the team will design the product are collected during stage one. Once the team has successfully completed this stage, it should know the nature of the opportunity and the stakeholders attached to it. When these elements change during the formulation of the set of design requirements and subsequent phases of development, the team will have to redo the work done in stage one and propagate these changes thorough out the rest of the process. Public demand and preferences and government regulations are especially likely to affect the market characteristics. It is important to notice that many of the other external factors discussed in this thesis could indirectly impact the public demand; however, for the purpose of this research the demand will be considered as a separate factor due to its potential large impact.

The user needs and their relative importance are determined during stages two and three. And they can be directly affected by changes occurring in the overall firm strategy and in the management's priorities. Many times these changes involve allocation of resources and modifications to the product's launch window. These are the external factors that could more easily be controlled by the design team, depending on their influence over the decisions made at the high levels of the organization. Once again changes to the user's needs might have to be propagated through the subsequent stages of the process.

Finally, the engineering specifications for the product are consolidated during the final three stages of requirements formulation. Not surprisingly, these can be affected by any of the external sources of uncertainty, including all the previously mentioned ones and the response of the firm's competitors, the legal status of the patents involved in the project, changes to availability of supplies, and changes in the readiness of the available technology.

Chapter 4

Validation Methods

Since there is abundant information in the literature regarding the sources of uncertainty that can increase the volatility of a set of design requirements and given that the evidence points to a strong connection between a highly volatile set of design requirements and a poor project outcome, we wanted to better understand the mechanics behind the evolution of the requirements during the early stages of design. With this purpose we carried out two different studies. First, we observed a number of experienced design teams during an advanced product design class to record their behavior and gather data about the characteristics of their respective sets of design requirements. The information was later searched for patterns and correlations. Afterwards, we also carried out two in-depth interviews with industry veterans regarding their experiences with successful and failed projects. Their opinions on the effects and consequences of the volatility of the products' design requirements were used to help interpret the empirical data and tie it to the conclusions found in the literature.

4.1 Analysis of Design Requirements

The data was gathered during twelve weeks in a graduate-level design course at MIT. The students were mid-career professionals with five to ten years of engineering and technology experience in industry. The students were grouped into eight teams with

the objective of designing, developing, and building an alpha prototype (Similar to the one shown in Figure 4-1) for a potentially commercial product. Each group was given a total budget of $800 for materials. Due to protocol issues at the end of the semester only the data from six of the teams was actually usable.

Figure 4-1: *Example of a Design and Development Class Project.*

Since this study required the quantification of the characteristics and changes done to the design requirements compiled by the different teams during an extended period of time and given that the products differed greatly from one another, it was critical to employ a consistent and standardized method of data gathering. Each team was asked to formulate a set of design requirements for their respective products. Figure 4-1 shows an example set of design requirements for a sports wrist watch. Each design requirement consisted of three parameters: the *Need* reflects the qualitative user need satisfied by the design requirement, such as *long power life*, the *Product Attributes* specified how the product can satisfy the user's need (i.e. time), and the *Engineering Specifications* quantified the specifications of the product that would fulfilled it (i.e. At least 2 years of battery life). To help maintain the team focus during develop-

ment, teams were encouraged to include a maximum of approximately fifteen core requirements rather than all the possible needs they could imagine for the product. In addition, the teams were asked to classify each design requirement depending on its relative importance, its level of difficulty, and as a latent or a explicit requirement. At the beginning of the course, each team was asked, after a brief explanation, to turn in the first set of design requirements (Set A). During the semester, each team turned in a total of seven sets of requirements. The updates were tracked not only qualitatively, but also quantitatively. At the end of the semester, a panel of eleven industry specialists rated the products in a number of categories to predict their potential market performance. The results were then compared to the characteristics of the product contracts, including the number of change and the number and type of requirements achieved with the final prototype.

Customer Needs	Product Attributes	Engineering Specifications
Comfortable	Dimensions	Case Diameter < 35 mm Case Thickness < 9 mm Band Length < 250 mm Band Width < 20 mm
Long Power Life	Time	> 2 years
Light	Weight	< 3 oz
Easy to clean	Materials	Plastic, Metal
Water Resistant	Pressure Resistance	Water Depth > 100 m
Good Value	Cost	< $100
Extra Features	Features	Chronometer, Calendar, Alarm
Type of Movement	Mechanism	Quartz

Customer Needs	Product Attributes	Engineering Specifications	
Comfortable	Dimensions	Case Diameter < 35 mm Case Thickness < 9 mm Band Length < 250 mm Band Width < 20 mm	
Long Power Life	Time	> 3 years	
Light Weight	**Weight**	**< 2 oz**	→ Changed
Easy to clean	Materials	Plastic, Metal	
Water Resistant	Pressure Resistance	Water Depth > 100 m	
Good Value	Cost	< $100	
~~Extra Features~~	~~Features~~	~~Chronometer, Calendar, Alarm~~	→ Changed
Type of Movement	Mechanism	Quartz	
Easy to Set Time and Date	**Time**	**Set Up Time < 10s**	→ Changed

Figure 4-2: *Examples of Change in a Product Contract.*

4.2 Interviews

In order to capture the subtleties of real development environments, two very in-depth interviews were carried out with industry veterans. Each of the interviewees have more than thirty years of experience as practitioners of design, engaged in both technical and executive roles. The main goal of the interviews was to find out what, in the experiences of the two interviewees, was the biggest challenge during the PDP and the formulation of design requirements. Additionally, we wanted to know if there were any characteristics in their respective fields of expertise that could make the conclusions in the literature invalid for a specific scenario.

The first interviewee worked for most of his career in the American auto industry. This industry is a classic example of a highly competitive sector, where intuitive, safe, and quality designs are highly regarded factors of success. The second interviewee's career has taken place in the defense industry. This industry is equally competitive, but focuses on the implementation of new technologies in cost efficient ways rather than on consumer products. Much of the information gathered during the interviews served to implicitly corroborate the facts used to create the framework presented in the previous section, but some of the answers are worthy of being explicitly presented in the following section as well.

The interviews took approximately one hour each. A week before, we asked both interviewees to consider projects in which they were personally involved and in which the formulation of design requirements was a major driver of the eventual success or failure of the product. The questions were mainly focused on their experiences during those projects.

Chapter 5

Results and Discussion

5.1 Analysis of Design Requirements

For the majority of the teams, the first version of the contract represented the baseline from which the progress of the development would be carried out. This can be discerned from the fact that all the teams, except one, incremented the number of requirement as they were presented with more information as shown in Figure 5-1. This was the expected trend. Making the decision to add a new requirement seems to required less effort than eliminating an unnecessary one. This can be due to two reasons: First, the initial elicitation of user needs was done very thoroughly and the team managed to capture the essence of the opportunity; and second - at least under these experimental conditions - the product contract was not binding and the team could easily decide not to pursuit any number of the design requirements without facing meaningful penalties.

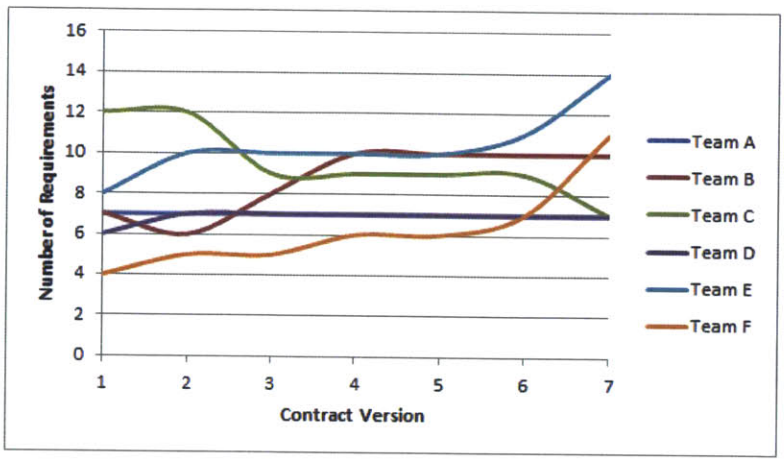

Figure 5-1: *Number of Design Requirements per Team.*

The teams' final score and the results from the subsequent analysis are presented in Figure 5-2. The numerical analysis did not yield anything statistically significant. perhaps because of the small sample size.

Team #	Score	Requirements		Priority						Risk						Latent		Changes
				High		Medium		Low		High		Medium		Low				
		Total	Achieved	Total	Achieved	Total	Achieved	Total	Achieved	Total	Achieved	Total	Achieved	Total	Achieved	Total	Achieved	
Team A	5.8	7	57%	57%	75%	14%	100%	29%	0%	43%	33%	14%	0%	43%	100%	0%	0%	0
Team B	3.6	10	50%	10%	100%	30%	67%	60%	33%	10%	100%	40%	0%	50%	80%	30%	33%	5
Team C	4.6	7	57%	57%	75%	43%	33%	0%	0%	0%	0%	71%	40%	29%	100%	14%	0%	6
Team D	5.1	7	57%	43%	67%	43%	67%	14%	0%	29%	50%	43%	67%	29%	50%	0%	0%	1
Team E	6.0	14	86%	29%	100%	21%	67%	50%	86%	0%	0%	36%	80%	64%	89%	64%	78%	6
Team F	5.5	11	45%	36%	75%	36%	25%	27%	33%	0%	0%	18%	100%	82%	33%	36%	50%	7
Correlation		0.45	0.63	0.26	0.03	-0.62	0.31	0.12	0.47	0.15	-0.60	-0.57	0.40	0.43	0.05	0.36	0.45	-0.13
Confidence		64%	85%	38%	5%	83%	46%	18%	67%	22%	82%	78%	58%	62%	8%	53%	64%	19%

Figure 5-2: *Analysis Performed on the Design Class's Product Contracts.*

Numbers rarely tell the whole story, and in this case the most revealing information was found instead by observing the behavior of the teams as they modified their respective sets of design requirements and the reasons behind these changes. There were four striking differences in the way the *best* (Team E) and *worst* (Team B) ranked teams formulated their respective sets of design requirements: First, Team E managed to identify a very promising opportunity; while Team B's opportunity was extremely vague. Second, the stakeholders considered by Team E were clearly defined from the start of the PDP, while the stakeholders considered by Team B changed several times during the development process. This allowed Team E to better allocate their resources on satisfying the correct set of defined needs. Team B's resources were diluted pursuing several paths that ended up going nowhere. Third, Team E chose a project that matched the technical skills of its members, while Team B's project scope was beyond the team's capabilities. This miscalculation forced Team B to abandon many of the most critical features from the final prototype reducing the attractiveness of their solution. Lastly, Team E spent far more time than Team B testing their prototype and receiving feedback from their potential customers. We do not exclude the possibility that other more subtle factors could have been involved in the outcome of the projects; however, in our opinion, the differences stated here show a definitive advantage of one team over the other, and are in clear alignment with the information found in the literature.

5.2 Interviews

When asked to think about the big obstacles that a company can face during the formulation of design requirements, interviewee number one referred to the prevalence, in the auto industry, to *play it safe* and how many of the failed projects in his experience were caused by excessive prudence. He also warned about the danger of having inflexible design requirements. He described the set of design requirements as a space that can change, but that ultimately must be stabilized by the research and the work done during the PDP. He also touched on the existence of very important,

but subjective design requirements, properties that are hard to define and tend to be immeasurable. When asked about the most prevalent characteristic among the most successful projects in which he was personally involved, he named almost immediately the strong customer focus. He also confirmed the fact that honing the original set of design requirements is a necessity, and receiving frequent feedback from the users is an extremely powerful tool. By staying in contact with the user it is possible for the design team to see beyond the numerical data and truly understand the emotional expectations of the customers. He referred to the mistake of trying to drive the development of a product solely by using rigid systems such as QFD. He talked about the value of really understanding what the customer needs and not what the firm assumes he needs. He dwelled on the importance of varying the design team dynamic according to the circumstances of development: a highly creative team should be the cornerstone of the formulation phase, but as the process moves on, decisive people should be introduce to the team in order to keep the process going forward. Finding ways of communicating the information among the different departments was also pinpointed as a major issue, given the power that management has over things they might not be able to fully understand, such as highly technical characteristics. Towards the end of the interview, he talked about the importance of being aware of potential changes to the governmental regulations in order to avoid being technologically and financially unprepared to react to the changes.

Interviewee number two explained how for any business the ultimate goal should be profitability, but how in order to achieve this, fulfilling the customer needs and keeping the different stakeholders happy is a fundamental pre-requirement. The main difference between the user oriented companies and firms that focus on business-to-business projects is, according to him, that when a company works for a client, it must start its design based on what the client thinks it needs and not on what the design team has found to be the root of the problem. Often clients will not only provide a set of needs, but will also try to provide a solution. It is the job of the design team to find the root cause of the issue and convince the client that the best solution might not be the one they originally wanted. He made an important distinction between

user and customer. A user is the person that uses and directly interacts with the product; while a customer is an entity with a need, a budget, and the ability to execute that budget. A way of seeing this in a very simplified form is to consider the case of the Air Force buying a new airplane. The Air Force is the customer and its needs must be considered, but it is the pilot and the mechanics who are the real users, and the product should be designed for them. Finally, the interviewee agreed with the literature and concluded that management is the one that should monitor the cost, time, and progress of the development without interfering with the creativity of the design team. "A good management program will keep all these axes under consideration, and at the same time will allow the flexibility to react to issues arising from changes in the circumstances".

Both interviewees agreed on the importance of understanding the user and saw the elicitation stage of the design requirements' formulation phase as a critical stepping stone for the rest of the process; however, they both warned against blindly consolidating the set of design requirements from the start, and instead they recommended constant evaluation to efficiently capture the changes that are required to make a better product. Change was in their experience a necessity of a good development process. Design teams can rarely understand all the complexities of the potential users' needs without frequent prototyping and users' feedback. They also, highlighted the importance of giving enough freedom to the design team to be creative, while at the same time keeping the cost of the project, the time of development, and the progress of the key tasks under the supervision of people capable of making the decisions. Lastly, they touched on the importance of gathering good intelligence to avoid being surprised with unexpected, and potentially costly, changes to the requirements of the product.

Chapter 6

Conclusions and Future Work

Reiterating, this thesis sought to answer two questions:

1. What factors are likely to increase the project's uncertainty during the formulation of the design requirements?

   Clearly the literature and the experts interviewed for this thesis agree on which events and conditions are most likely to increase the uncertainty of a product development project. Internally, the orientation, technical skills, and dynamic of the design team are major sources of uncertainty. If wrong, these conditions can have a tremendously harmful effect on the completeness and accuracy of the set of design requirements. While externally, events that cause changes to the market demand, government's regulations, firm's overall strategy, legal status of the patented technology, competitors' stances, management, suppliers' status, and available technology can have dangerous disrupting effects on the PDP and should be constantly monitored.

2. What strategies can be taken to stabilize the set of design requirements?

   Despite the variety of benchmarks described in the literature to measure the final outcome of the PDP, there seems to be consensus on the fact that success can only be attained by the product's capacity to satisfy the needs of the primary stakeholders. This can only happen when the opportunity has been clearly defined and the stakeholders have been thoroughly studied. Usually companies

rely excessively on their marketing departments to carry out the bulk of the market studies, but by doing this they run the risk of over constraining the design team which, as the main actor in the PDP, holds the responsibility of carrying out the task of understanding and satisfying the customers' expectations. Therefore, it is in the best interest of the managers and team leaders to include the design team on the planning phase for future developments as much as possible. This strategy promotes empathy between the engineers and the users, which combined with their natural creativity and technical skills leads to better product design and promotes the development of more accurate solutions.

In addition to promoting the integration of the different departments within the company, another way of nurturing the connection of the design team to the users is to foment the formulation of an insightful and complete set of design requirements. These requirements are the conduits through which the information flows from the designer's observations and is distilled into useful engineering specifications. As the main line of communications between the two entities, and the platform upon which the product will be built, it is hard to overestimate its importance as a major component of the PDP. Managers and team leaders should strive to avoid taking any action that could have a disruptive effect on the formulation phase.

Of course meddling and overseeing are two completely different things and should not be confused. A complete relaxation of the evaluating mechanisms might afford the design team a more comfortable environment in which to think and create, but considering the importance of prompt decision making in the reduction of cost and time of development, doing so could entirely dull the competitive edge of the firm. The best strategy is to evaluate the PDP and the performance of the design team after the completion of each stage. In this way their progress can be better linked to the cost and time of development.

Even though the set of design requirements is written in a product contract, its contents are not immune to change. Evidently, as the team reaches the end of

the project, the likelihood of the set changing should be significantly reduced in comparison to the highly volatile conditions of the beginning of the process. Most of the changes to the set are a normal part of the learning process that takes place within the design team, but not all changes are wanted or expected; and this uncertainty can prevent the firm from reacting with the swiftness and decisiveness required to mitigate their harmful propagation and the associated costs.

Good intelligence is the best weapon in the firm's arsenal against uncertainty and volatility; and since its collection can be seriously impaired by a dysfunctional design team, it is critical for the team leader and management to monitor its orientation, dynamic, and technical competence during the full run of the PDP. A customer-oriented, appropriately diverse, and technically skilled design team is an invaluable asset for the firm and should be treasured. Time-oriented, homogeneous, and technically unskilled teams are an immense liability and should be rapidly purged of their destructive elements. Armed with an effective and adaptable design team, the company can use the gathered data and the flexibility of the development process to shield the already achieved results from harmful changes.

Each one of these elements constitutes an important part of the development environment, and as such they deserve to be included in the descriptive framework developed for this thesis. Certain aspects have been simplified and the use of educated assumptions is undeniable; however, as far as exploring and describing in a comprehensive manner the reality of the PDP in its early stages the framework remains a true reflection of reality. This research is only the beginning, and with much still to be done we hope that, as this research continues to be developed, the evidence gathered through the qualitative methods presented here will give way to more solid approaches.

In the future, it would be useful to improve the analysis of the work done in the product design class. Given not only the experience of the people involved, but also

the variety of projects, we are confident on the existence of valuable information yet to be discovered. Increasing the granularity of the collection of information from the product contracts would be a worthy first step in the right direction; additionally, more feedback on the validity of the framework should be obtained. Interviewing more experts from other industries would be a good way of comparing the difference between similarly sized but overall different companies. We cannot stress enough the value of the information collected in this way. The review of the literature should be expanded to also include historical evidence of the external sources of uncertainty that have affected the development process of past projects, to better understand the way successful and failed companies have dealt with them throughout the years.

After enhancing the collection methods already used here, the next step would naturally be to advance from a purely descriptive to a more prescriptive research. A mathematical model should be develop to link the completion of key tasks in the process, the time of development, and the associated costs to the levels of uncertainty and volatility. It is the ultimate goal of this research to culminate with the creation of an assessment tool that firms could use to streamline their PDP and in this way reduce the unnecessary waste of resources and time. The final step would be to test the assessment tool in a control environment such as the one provide by the product design class referenced in the research, and then in a real-life environment where its accuracy and benefits could be truly measured.

Bibliography

[1] Kevin B. Hendricks and Vinod R. Singhal. Delays in new product introductions and the market value of the firm: The consequences of being late to the market. *Management Science*, 43:422–436, 1997.

[2] Abbie Griffin and John R. Hauser. Integrating r&d and marketing: A review and analysis of the literature. *Journal of Product Innovation Management*, 13:191–215, 1996.

[3] Josef Oehmen and Alison Olechowski. Design protocols and risk management in large complex projects with applications to clean water and energy systems.

[4] Edith Wilson. Improving market success rates through better product definition. *World Class Design to Manufacture*, 1:13–15, 1994.

[5] Jeffrey Liker. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill, 2003.

[6] Anil Kaul and Vithala R. Rao. Research for product positioning and design descisions: An integrative review. *International Journal of Research in Marketing*, 12:293–320, 1995.

[7] John Pearley Huffman. 5 most notorious recalls of all time, 2013.

[8] Paul Sloane. A lesson in innovation: Why did the segway fail?, May 2012.

[9] James Tate. The 100 hottest cars of all time, 2011.

[10] Erik Jan Hultink, Abbie Griffin, Susan Hart, and Henry S. J. Robben. Industrial new product launch strategies and product development performance. *Journal of Product Innovation Management*, 14:243–257, 1997.

[11] Joseph A. Goguen and Charlotte Lindt. Techniques for requirements elicitation. In *Procedings Requirements Engineering '93*, 1993.

[12] Rolf A. Faste. Perceiving needs. *Society of Automotive Engineers*, 1987.

[13] John R. Hauser and Don Clausing. The house of quality. *Harvard Business Review*, May-June, 1988.

[14] Deborah Dougherty. Interpretative barriers to succesful product innovation in large firms. *Organization Science*, 3:179–202, 1992.

[15] Vassilis Agouridas, Alison McKay, Henri Winand, and Alan de Pennington. Advanced product planning: A comprehensive process for systemic definition of new product requirements. *Requirements Eng*, 13:19–48, 2008.

[16] Peter H. Bloch. Seeking the ideal form: Product design and consumer response. *Journal of Marketing*, 59:16–29, 1995.

[17] Amaresh Chakrabarti, Stefan Morgenstern, and Helge Knaab. Identification and application of requirements and their impact on the design process: A protocol study. *Research in Engineering Design*, 15:22–39, 2004.

[18] David Baxter, James Gao, Keith Case, Jenny Harding, Bob Young, Sean Cochrane, and Shilpa Dani. A framework to integrate design knowledge reuse and requirements management in engineering design. *Robotics and Computer-Integrated Manufacturing*, 24:585–593, 2008.

[19] V Agouridas, H Winand, A McKay, and A de Pennington. Early alignment of design requirements with stakeholder needs. *J. Engineering Manufacture*, 220:1483–1507, 2006.

[20] Stephanie Houde and Charles Hill. What do prototypes prototype? Technical report, Apple Computer, Inc., 1995.

[21] Monica Giffin, Olivier de Weck, Gergana Bounova, Rene Keller, Claudia Eckert, and John Clarkson. Change propagation analysis in complex technical systems. In *Proceedings of IDETC/CIE 2007*, 2007.

[22] Andres Segismundo and Paulo A. Cauchick Miguel. Risk management in the development of new product: A review and classification of the literature. *Product: Management & Development*, 6:45–51, 2008.

[23] Christopher D. Ittner and David F. Larcker. Quality strategy, strategic control system, and organizational performance. *Accounting, Organizations and Society*, 22:293–314, 1997.

[24] Gary Burchill and Charles H. Fine. Time versus market orientation in product concept development: Empirically-based theory generation. *Management Science*, 43:465–478, 1997.

[25] Shona L. Brown and Kathleen M. Eisenhardt. Product development: Past reasearch, present findings, and future directions. *Academy of Management Review*, 20:343–378, 1995.

[26] Deborah Gladstein Ancona and David F. Caldwell. Demography and design: Predictors of new product team performance. *Organization Science*, 3:321–341, 1992.

[27] Daniel Capaldo Amaral and Henrique Rozenfeld. Explicit knowledge management on the product development process. *Product: Management & Development*, 1:49–58, 2001.

[28] Christine Moorman and Anne S. Miner. The impact of organizational memory on new product performance and creativity. *Journal of Marketing Research*, 34:91–106, 1997.

[29] David G. Hoopes and Steven Postrel. Shared knowledge, "glitches," and product development performance. *Strategic Management Journal*, 20:837–865, 1999.

[30] Paul R. Carlile. A pragmatic view of knowledge and bounderies: Boundary objects in new product development. *Organization Science*, 13:442–455, 2002.

[31] Clayton M. Christensen and Joseph L. Bower. Customer power, strategic investment, and the failure of leading firms. *Strategic Management Journal*, 17:197–218, 1996.

[32] Marcelo Gitirana Gomes Ferreira, Fernando Antonio Forcellini, Osmar Possamal, Adriano Heemann, and Antonio Domingues Brasil. A review of strategies for knowledge management in the early stages of the product development process. *Product: Management & Development*, 4:105–113, 2006.

[33] Marco Iansiti. Shooting the rapids: Managing product development in turbulent enviroments. *California Management Review*, 38:37–58, 1995.

[34] Hubert Gatignon and Jean-Marc Xuereb. Strategic orientation of the firm and new product prerformance. Technical report, INSEAD, June 1995.

[35] Paul S. Adler, Avi Mandelbaum, Vien Nguyen, and Elizabeth Scwerer. From project to process management: An empirically-based framework for analyzing product development time. *Management Science*, 41:458–484, 1995.

[36] Karl T. Ulrich and Steven D. Eppinger. *Product Design and Development.* McGraw-Hill, 2011.

[37] Crispin Hales. *Analysis of the Engineering Design Process in an Industrial Context.* Gants Hill Publications, 1991.

[38] Paulo Carlos Kaminski and Renato Vizioli. Balanced scorcard as a driver to the corporative database use on product development process. *Product: Management & Development*, 1:17–27, 2002.

[39] Marcia Elisa Echeveste, Jose Luis Duarte Ribeiro, and Michel Jose Anzanello. A metric system for feature and cost control during product development. *Product: Management & Development*, 3:147–155, 2005.

[40] Hirotaka Takeuchi and Ikujiro Nonaka. The new new product development game. *Harvard Business Review*, January-February:137–146, 1986.

[41] Sean Hansen, Nicholas Berente, and Kalle Lyytinen. Requirements in the 21st century: Current practice and emerging trends. *Design Requirements Workshop*, 14:44–87, 2009.

[42] Viswanathan Krishnan, Steven D. Eppinger, and Daniel E. Whitney. A model-based framework to overlap product development activities. *Management Science*, 43:437–451, 1997.

[43] M Cross and S Sivaloganathan. A methodology for developing company-specific design process models. *J. Engineering Manufacture*, 219:265–282, 2005.

[44] Martin Stacey and Claudia Eckert. Reshaping the box: Creative designing as constraint management. *Int. J. Product Development*, 11:241–255, 2010.

[45] Luis Gustavo Scrassolo Martini and Luis Gonzaga Trabasso. Product strategic development: Preliminary overview. *Product: Management & Development*, 4:5–12, 2006.

[46] Jane Coughlan and Robert D. Macredie. Effective communication in requirements elicitation: A comparison of methodologies. *Requirements Eng*, 7:47–60, 2002.