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Quantification of Technology Innovation Using a Risk-Based Framework

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***Abstract*—**There is significant interest in achieving technology innovation through new product development activities. It is recognized, however, that traditional project management practices focused only on performance, cost, and schedule attributes, can often lead to risk mitigation strategies that limit new technology innovation. In this paper, a new approach is proposed for formally managing and quantifying technology innovation. This approach uses a risk-based framework that simultaneously optimizes innovation attributes along with traditional project management and system engineering attributes. To demonstrate the efficacy of the new risk-based approach, a comprehensive product development experiment was conducted. This experiment simultaneously managed the innovation risks and the product delivery risks through the proposed risk-based framework. Quantitative metrics for technology innovation were tracked and the experimental results indicate that the risk-based approach can simultaneously achieve both project deliverable and innovation objectives.

***Keywords*—**innovation, risk assessment, product development, technology management.

I. Introduction

IT is widely recognized that technology innovation occurs when new technologies are adopted and inserted during the new product development cycle [1]. Conversely, it has also been observed [2] that traditional project management methodologies can drive product developers to reject new technologies in order to mitigate the risks associated with meeting performance, cost, and schedule objectives. This counteracting paradigm often leads institutions to fall short of their technology innovation objectives and can subsequently have a negative impact on the research and development capabilities within their organizations [3]. In order to manage this inherent trade-off between technology innovation and new product delivery objectives, institutions often establish independent research and development (IRAD) programs to ensure that new and innovative technologies are being developed in parallel to the product development cycles. In order for IRAD strategies to succeed, however, institutions generally need to adopt formal technology management processes [4] to help ensure that their new technologies are inserted into new products and thereby minimize the probability that innovative technologies will fail to be adopted.

In this paper, a new technology management approach is proposed, whereby technology innovation is treated as an inherent aspect of the product development cycle. Specifically, we propose a risk-based framework for new product development that simultaneously considers both quantitative innovation objectives and quantitative product delivery objectives (cost, schedule, performance). This approach enables technology managers to establish formal quantitative technology innovation objectives and to track and monitor these during an integrated product development cycle. It is hypothesized that such an approach will increase the likelihood of new technology acceptance and thereby accelerate the pace of technology innovation.

In subsequent sections of this paper, we first describe the theoretical foundations of a quantitative framework for simultaneously managing project risk and innovation risk. We then describe a controlled experiment to assess the efficacy of the new risk-based approach. In this experiment, independent variables were established for both product delivery and innovation objectives and these variables were tracked throughout the course of a multi-year product development cycle. The compilations of these experimental results were used to demonstrate whether or not the new product development efforts could achieve all project requirements (cost, schedule, and performance), while simultaneously achieving the quantitative innovation objectives. In the closing section of this paper, a recommendation is made that further theoretical and experimental efforts be conducted in order to fully test the hypothesis that such a quantitative risk-based approach will consistently accelerate the pace of technology innovation.

II. Theoretical framework

Risk analysis and the related quantitative methods have been the subject of extensive scientific research [5]. Probabilistic risk-based methodologies have been applied to problems ranging from construction activities [6] to high-consequence scenario analyses [7]. In quantitative risk assessment, risk is measured as the combinatorial association of the probability of occurrence of an event with the associated consequences of the event. Using the generally accepted expression for risk [8], let us first define the risk of occurrence of an event E as follows:

$$R_E = L_E \sum_{i=1}^{N_E} c_i p_i \tag{1}$$

where R_E is the risk associated with event E, L_E is the likelihood of event E, the c_i are a set of undesirable consequences associated with event E, and the p_i are the probabilities of the respective consequences. N_E is the number

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of consequences that are being assessed by the risk analyst. Using traditional project management principles, one can now define the cost, schedule, and performance risks associated with a product development effort as follows:

$$R_C = L_C \sum_{i=1}^{N_C} c_i p_i\,;\;\; R_S = L_S \sum_{i=1}^{N_S} c_i p_i\,;\;\; R_P = L_P \sum_{i=1}^{N_P} c_i p_i \quad (2)$$

where R_C is the risk of exceeding project cost requirements, R_E is the risk of missing project schedule requirements, and R_p is the risk of not meeting the technical performance requirements. Prior efforts in assessing the risk of new product developments have only focused on minimizing the probabilistic risk of the cost, schedule, and performance attributes as per (2). In the approach herein, consider the introduction of innovation risk as follows:

$$R_I = L_I \sum_{i=1}^{N_I} c_i p_i \quad (3)$$

where R_I is the risk that the new product development efforts will not meet institutional innovation objectives. It is important to note that the innovation consequences, c_i, in (3) need to be expressed as quantitative innovation metrics. Examples of innovation metrics can be found in [9]. In the next section, three (3) quantitative innovation metrics for tracking product developments will be further defined.

In order to establish a framework for simultaneously integrating both project management risks and innovation risks, the Product Development Risk, R_{PD}, can now be defined as:

$$R_{PD} = f(R_C, R_S, R_P, R_I) \quad (4)$$

where f represents the probabilistic function of the cost, schedule, performance, and innovation risk variables. Because each of the risks expressed in the functional are generally statistically-dependent random variables, a closed-form deterministic solution to this optimization problem cannot always be expressed. However, modern quantitative analytic tools such as Critical Path Methods (CPM) [10], and Fault Tree Analysis (FTA) [11] can be used to gain insight into appropriate risk mitigation strategies. Equation (4) can therefore be used as a part of an analytical framework, as depicted in Figure 1, to enable the simultaneous analysis of cost, schedule, performance, and innovation risks of a new product development activity.

III. EXPERIMENTAL APPROACH

In this section, a multi-year product development experiment is defined in order to test the efficacy of the proposed theoretical approach. The experiment was designed to simultaneously test both the traditional project management attributes (technical performance, cost, schedule) and the

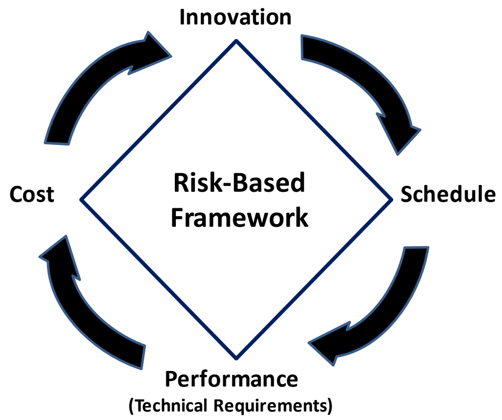

Fig. 1: Risk-based framework for quantifying technology innovation during new product development activities.

quantitative innovation attributes of an actual product development effort. In this experiment, the product development effort was focused on the realization of an acceleration-switch ('g' switch) for a specific new application. In order to implement the risk-based framework described above, a detailed set of operational requirements and innovation objectives were established. The operational requirements were documented in a requirements and specifications document that included physical and electrical characteristics. The innovation requirements were driven by an institutional desire to mature silicon micro-electro-mechanical (MEMS) technologies, not only for acceleration switches, but for a broad range of novel applications. This technology innovation experiment was performed in a collaborative research environment that was previously reported in Reference [12].

In order to establish independent risk variables for the experiment, two separate technology options for the acceleration-switch were established and tracked in parallel. The first technology option, referred to as the Low-Innovation Technology Option (LITO), was based on a mature conventionally-machined acceleration-switch technology, as shown in Figure 2. The LITO was based on commercial-off-the-shelf (COTS) technology that was already in production for applications such as automobile air-bags. Because of the new performance requirements for the intended application, the COTS technology did carry certain technical risks. Specifically, technical requirements such as off-axis sensitivity, on-axis threshold consistency, and electro-mechanical chatter had not been previously characterized. Thus, the LITO was effectively at a Technology Readiness Level [c.f. 14] of *TRL*=5 for the new application and required some relatively low-risk engineering modifications and a test-evaluation-qualification activity to ensure it could meet all new performance requirements.

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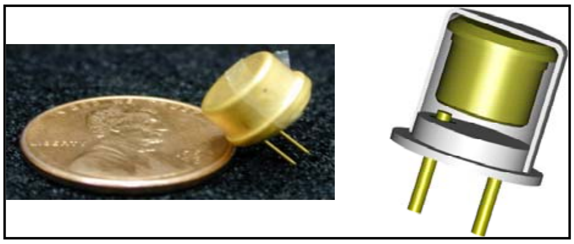

Fig. 2: Depiction of the Low-Innovation Technology Option (LITO) studied in this experiment. This device is a commercial-off-the-shelf acceleration switch that uses a conventionally-machined spring-mass mechanism.

The second technology option considered in this study, referred to as the High-Innovation Technology Option (HITO), was based on a novel silicon MEMS design [13], and is depicted in Figure 3. At the start of this experiment, this MEMS g-switch was in the conceptual design phase, having never been prototyped nor tested, and was at a starting readiness level of *TRL*-2. Significant efforts were required to mature the HITO including; detailed electro-mechanical design and analysis, silicon die fabrication maturation, packaging design and development, and establishment of new test processes, equipment, and fixtures. Hence the High-Innovation Technology Option carried significant technical risks but offered the potential to substantially accelerate the Institution's capabilities and innovations in MEMS technologies.

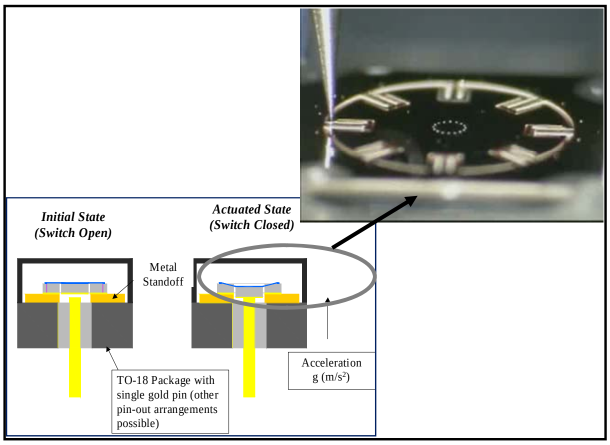

Fig. 3: Depiction of the High-Innovation Technology Option (HITO) studied in this experiment. This device is a micro-electro-mechanical (MEMS) acceleration switch based on silicon micro-machining technology.

In this experiment, a fixed and common schedule was established for the product development effort. Specifically, an 18-month development schedule was established, culminating in a Critical Design Review (CDR) to down-select the technology option that would go into full-scale production. Using the risk-based approach described above, independent cost requirements were established for the LITO and the HITO. Furthermore, three (3) quantitative innovation metrics were established and tracked for the High-Innovation Option. The first innovation metric, referred herein as the Technology Maturation Rate (*TMR*), is defined as:

$$TMR = \frac{TRL_f - TRL_i}{M} \quad (5)$$

where TRL_f is the Technology Readiness Level [14] at the completion of the experiment, TRL_i is the Technology Readiness Level at the start of the experiment, and M is the duration of the experiment in years. In the experiment, interim design reviews were held periodically throughout the M=1.5 year experiment in order to assess the *TRL*'s of the acceleration switches. The innovation goal set for this experiment was to achieve a *TRL*=6 for the HITO accelerometer-switches by the end of the 1.5 year development effort, or equivalently, to achieve a *TMR*>2.6.

The second innovation metric monitored during this experiment was the Prototype Development Cycle Time, PDCT, defined as:

$$PDCT = T_d + T_b + T_t + T_a \quad (6)$$

where T_d is the time required to design the prototype, T_b was the time required to build a prototype lot, T_t is the time to test the prototype lot, and T_a is the time required to analyze the performance of the prototypes. The innovation objective set for *PDCT* was to demonstrate that the cycle time for the HITO could be reduced to less than 3 months. Since the LITO cycle time was approximately 1 year, this would represent a significant innovation achievement.

The third innovation metric monitored during this experiment was the Prototype Production Yield, *PPY*, of the prototype acceleration- switches, defined as:

$$PPY = 100 * \frac{K_o}{K_b} \quad (7)$$

where K_o is the number of acceleration-switches that are operational in a prototype production run and K_b is the total number of acceleration-switches built in the prototype production run. The innovation goal of this experiment was to achieve *PPY*>80%. The production yield is a particularly important parameter from an innovation perspective, since it quantifies the advantages of adopting silicon- wafer batch fabrication processes.

IV. Results

Product development activities for the LITO and the HITO acceleration switches were successfully executed over an 18 month period. Figure 4 illustrates the high-level schedule for the execution of the HITO product development efforts. Also illustrated in Figure 4 are the major technical milestones and technical innovations achieved during the new product development experiment.

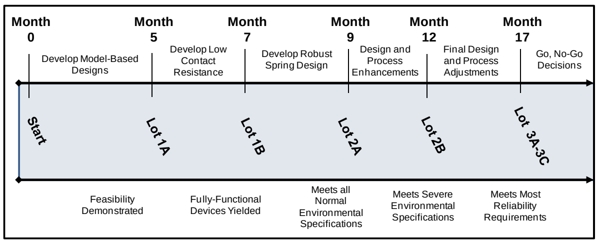

Fig. 4: Product development schedule for the High-Innovation Technology Option (HITO). Indicated along the top of the chart are the key design development activities. Along the middle of the chart are the major milestones for the prototype production lots. Along the bottom of the chart are the significant innovation indicators.

During the course of the experimental product development effort, formal technological readiness assessments were performed. These assessments were made by a group of individuals that represented both the product end-user community ('customer') and the product developers ('supplier'). These assessments utilized the standard 9-level technology readiness scale (*TRL*'s). The *TRL* success criteria at each level was established by comparing the prototype device test results to the relevant and operational environments specified in the product technical requirements documents. Figure 5, plots the results of the technology readiness assessments for the HITO accelerometer switch during the 18 month experiment. The HITO devices advanced from an initial *TRL*=2 to a mature level of *TRL*=7 at the end of the experiment. Using (5), the HITO accelerometer switch attained a calculated Technology Maturation Rate of *TMR*=3.33 *TRL*/yr over the duration of the experiment. This is a very high rate of technology maturation and clearly demonstrates that the experiment was able to meet the first quantitative innovation objective.

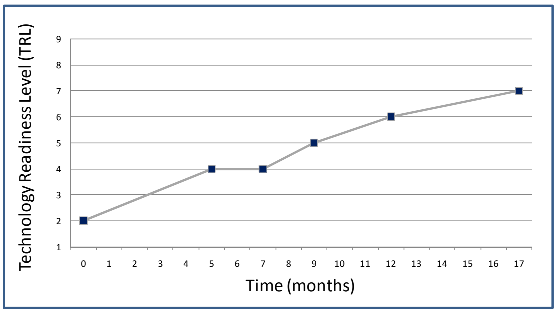

Fig. 5: Technology readiness assessment results from the High-Innovation Technology Option (HITO) experiment. The HITO attained a Technology Maturation Rate of 3.3 TRL/yr.

From the schedule information contained in Figure 4 and measurements of the actual cycle times per (6), it is now straightforward to evaluate the second quantitative innovation objective. Figure 6 plots the Product Development Cycle Times (*PDCT*) measured for each prototype lot that was design-built-tested-analyzed during this experiment. The data indicate that there was generally a trend towards decreasing cycle times throughout the experiment. The observed reduction in cycle times during the first 9 months can be attributed to efficiencies realized from the extensive use of modeling and simulation during the design-test-analysis phases. The increase in cycle time during month 12 was attributed to the discovery of a new mechanical wear phenomenon in the silicon device that required additional tests and analyses. The reduction in cycle time over the last 5 months of the experiment was attributed to batch process production efficiencies that allowed multiple prototype lots to be partially manufactured in parallel. In summary, the results indicate that the experiment successfully met the quantative innovation objective of *PDCT* less than <3 months.

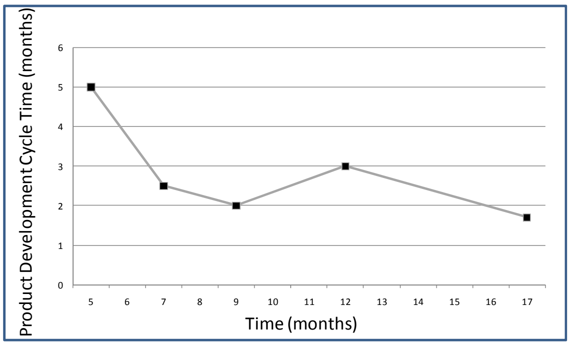

Fig. 6: Measurements of the Product Development Cycle Time (PDCT) of the HITO devices over the duration of the 18 month experiment.

As the final quantative measure of innovation during this experiment, the Prototype Production Yield, *PPY*, as per (7), was evaluated. Due to the batch fabrication processes associated with the HITO devices, several thousand prototypes were built during the course of the experiment. Of these, a total of approximately 850 HITO devices were fully characterized to determine operational yield. In Figure 7, the value of *PPY* that was determined for each of the prototype fabrication runs is plotted. The data indicate a significant improvement trend in prototype device yields. The data also indicate the experiment successfully met the quantitative innovation objective of *PPY*>80%.

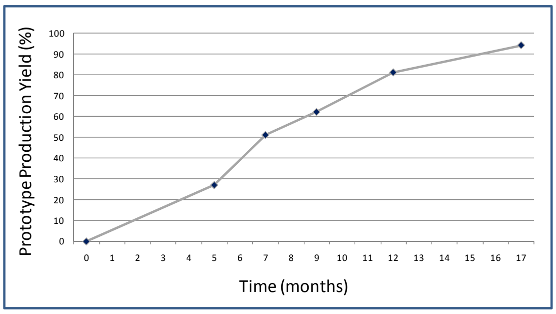

Fig. 7: Operational yield of the HITO devices obtained from each prototype production lot during the course of the 18 month experiment.

In summarizing the above, it is evident that the experiment successfully demonstrated that quantitative innovation objectives can be measured and achieved during a risk-based product development effort. It should be noted that both the HITO and LITO product development efforts were successfully completed on-budget and on-schedule, thereby meeting programmatic risk objectives. The LITO devices successfully met all quantative technical performance requirements for the new application. The HITO devices also met all quantitative technical performance requirements, with the exception of a long-term vibration reliability specification. During a series of long-term vibration reliability tests, it was observed that the wear mechanism discovered in Month 12 could cause premature failures of the devices under certain environmental conditions. During the culminating Critical Design Review, it was determined that the long-term reliability of the HITO device represented a potentially unacceptable product lifecycle risk. As a result, the final risk-based decision of this experiment was to put only the LITO devices into full-scale production for the intended application. Anecdotally, the Institution did later benefit from this risk-based innovation experiment and successfully deployed the novel MEMS technologies in subsequent product development efforts. In summary, this experimental case study demonstrated that a risk-based innovation framework can be used to achieve quantative product delivery objectives while simultaneously meeting quantitative innovation objectives.

V. Conclusion

In this paper, a new risk-based technology management approach has been proposed wherein technology innovation is treated as an inherent aspect of the product development cycle. Specifically, a risk-based framework for new product development activities that simultaneously considers both quantitative innovation objectives and quantitative product delivery objectives (cost, schedule, performance) was introduced. This approach enables technology managers to establish formal quantitative technology innovation objectives and to track and monitor these during an integrated product development cycle. In this study, a theoretical quantitative framework for simultaneously managing project risk and innovation risk was established. Controlled experiments were conducted to assess the efficacy of the new risk-based approach. In this experiment, independent variables were established for both product delivery and innovation objectives and these variables were tracked throughout the course of a multi-year product development activity. A compilation of the experimental results successfully showed that new product development efforts could achieve all project delivery requirements while simultaneously achieving the quantitative innovation objectives. While this experiment represents a valid case study, this experiment alone is insufficient to prove the hypothesis that such a quantitative risk-based approach will consistently accelerate the pace of technology innovation. It is therefore recommended that further theoretical and experimental efforts be conducted in order to fully test the efficacy of the proposed risk-based technology innovation framework.

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