LAI Paper Series
"Lean Product Development for Practitioners"

Risk Management in Lean PD

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1 About LAI

The Lean Advancement Initiative (LAI) at MIT, together with its Educational Network (EdNet), offers organizational members from industry, government, and academia the newest and best thinking, products, and tools related to lean enterprise architecting and transformation. LAI is a unique research consortium that provides a neutral forum for sharing research findings, lessons learned, and best practices.

LAI offers:
- unique opportunities to engage with customers, suppliers, and partners to solve problems and share organizational transformation experiences
- a portfolio of thought-provoking knowledge exchange events and meetings
- innovative enterprise transformation products, tools, and methodologies

LAI researches, develops, and promulgates practices, tools, and knowledge that enable and accelerate enterprise transformation. LAI accelerates lean deployment through identified best practices, shared communication, common goals, and strategic and implementation tools honed from collaborative experience. LAI also promotes cooperation at all levels and facets of an enterprise to eliminate traditional barriers to improving industry and government teamwork.

The greatest benefits of lean result when the operating, technical, business, and administrative units of an enterprise strive for enterprise-wide lean performance. LAI is completing its fifth Enterprise Value phase, during which LAI has engaged in transforming aerospace entities into total lean enterprises and delivered more value to all stakeholders than would have been possible through conventional approaches.

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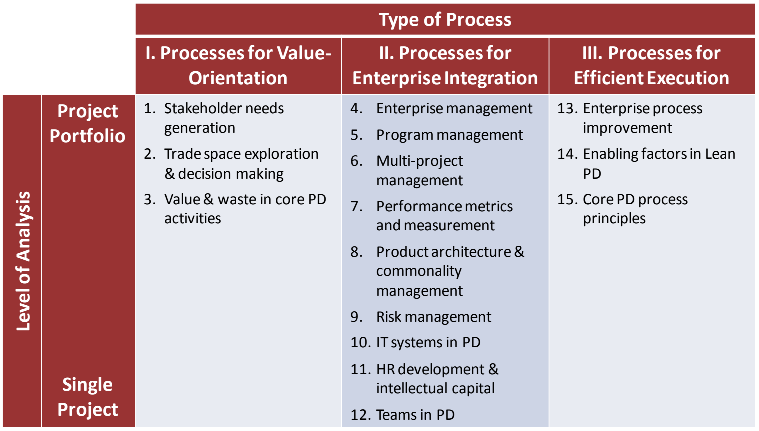
2 About this Series

A vast amount of research has been conducted at MIT´s Lean Advancement Initiative (LAI) on Lean Product Development in the last 15 years. For the first time, this series of papers makes this research accessible to practitioners in a condensed form.

The aim is to provide an application-oriented, readable, concise and comprehensive overview of the main fields of Lean Product Development. The papers follow LAI´s understanding and philosophy regarding Lean Management concepts and especially their integration into large and complex Enterprise settings.

The papers draw mainly on the research done by LAI. Where necessary to ensure a comprehensive presentation of a topic, findings of other researchers and research groups from the field of Lean Product Development are integrated into the papers.



		Type of Process		
		I. Processes for Value-Orientation	II. Processes for Enterprise Integration	III. Processes for Efficient Execution
Level of Analysis	Project Portfolio Single Project	1. Stakeholder needs generation 2. Trade space exploration & decision making 3. Value & waste in core PD activities	4. Enterprise management 5. Program management 6. Multi-project management 7. Performance metrics and measurement 8. Product architecture & commonality management 9. Risk management 10. IT systems in PD 11. HR development & intellectual capital 12. Teams in PD	13. Enterprise process improvement 14. Enabling factors in Lean PD 15. Core PD process principles

Figure 1: Topics of the Paper Series - LAI's Three Main Areas of Lean Product Development

The series focuses on 15 topics in three major areas of Lean Product Development that LAI identified (see Figure 1). The processes span the space from single project to project portfolio management. This paper addresses topic 9, Risk Management.

2.1 I: Processes for Value-orientation

The processes for value-orientation address those types of processes that ensure a focus on the creation of value and the elimination of waste in Lean Product Development. This covers the areas of stakeholder needs generation, trade space exploration and decision making, as well as the identification and handling of value and waste in the core PD processes.

2.2 II: Processes for Enterprise Integration

Enterprise Integration is one of the main challenges in developing a Lean Enterprise. Product Development plays a central role in this integration effort, as it interfaces with all main Enterprise processes. This therefore larger group consists of the processes of enterprise, program and multi-project management, performance metrics and measurement, product architecture and commonality management, risk management, IT systems, HR development and human capital, and teams in Product Development.

2.3 III: Processes for Efficient Execution

This group addresses the challenges surrounding the efficient execution of PD processes. It includes the relationship of PD to overall Enterprise process improvement initiatives, enabling organizational factors within Lean PD, as well as addressing alternative Lean PD core process principles.

3 Introduction to the Challenges in Lean PD Risk Management

The two core challenges of risk management are finding the optimum balance a) between the cost of carrying risks vs. the cost of mitigating risks and b) between a risk that is taken with a certain development project and the return that is expected from the project.

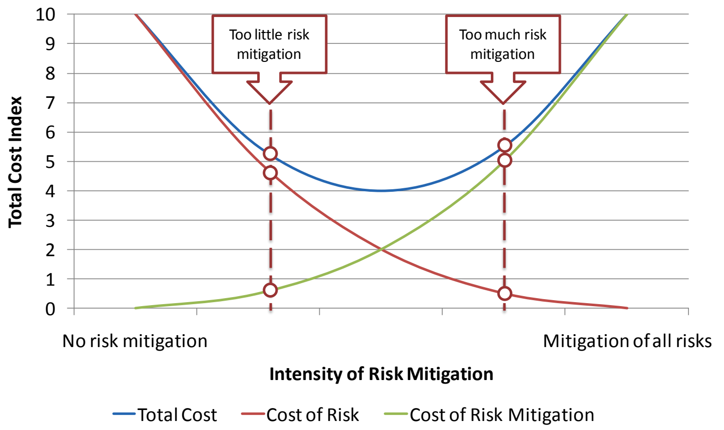


Figure 2: Trade-off between cost of risks and cost of risk mitigation

A complete absence of risk management will minimize the cost of risk mitigation measures – no backup development capacity, no review meetings, no quality control incur no direct cost. However, the project becomes very vulnerable towards uncertainties: If a development task turns out to be more complex than previously anticipated and no backup capacity can be brought to bear, the entire project might be delayed and cost incurred through idle capacities, penalty payments towards the customer for delays or opportunity cost for lost customers and market share. The same may happen for less-than-perfect coordination between different engineers and departments, or erroneous designs that would otherwise have been uncovered in review meetings or quality checks. On the other hand, excess backup capacity, reviews and quality controls bind more resources and cost more money than they save. Good risk management helps to strike the right balance between minimizing risk and the cost of doing so.

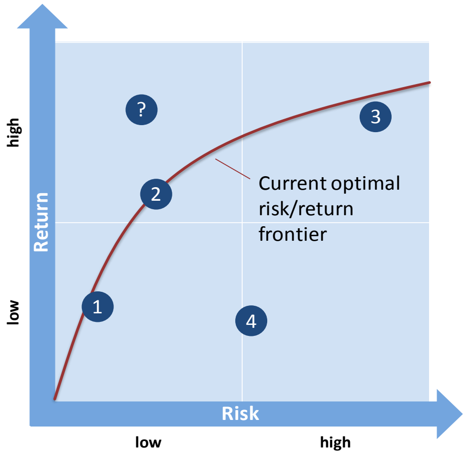


Figure 3: Deciding on an acceptable risk / return balance

After minimizing the overall risk as much as is sensible, the question remains what the right level of risk is that is still acceptable for a project to be attractive. While the goal for every single project is to minimize its overall risk, projects are in general exposed to different levels of uncertainty: Some might involve more innovative technologies or technologies that the company is not familiar with; some might address new markets where the exact customer requirements are unclear; and others might just be a lot bigger than usual and therefore have a much more significant impact if they fail. The goal is to find projects that have the right balance of risk and return, as would be the case with any other investments (e.g. a portfolio of stocks and bonds). As depicted in Figure 3, projects 1, 2 and 3 are all exposed to different levels of risk: Judging by riskiness only, project 1 would be the clear winner; however, it does not promise the same return as project 3. Project 1 might be an incremental improvement to a long-established product that is close to the end of its lifecycle in the market. Project 2 might be the project to develop the replacement product, involving new technologies, whereas 3 might be a jump into a new market requiring significant up-front investments. Project 4 on the other hand only has the same expected return as project 1, but at a much higher risk. If the risk of the project cannot be reduced significantly, it would not be an attractive option to pursue further. Caution has to be exercised with projects that seem to promise high returns at little risk: while they might exist, the chances are equally high that some important factor has been overlooked in the risk assessment. Following this reasoning, risk management can also be interpreted as opportunity management: For a given return on investment, or opportunity, that an organization aims at, what is the option that provides this opportunity at the minimum risk?

Assuming that the overall goal of PD is to achieve the targets of high product quality, low product cost, short development time and low development cost (see e.g. (Ulrich and Eppinger, 1995)), these goals also constitute the main categories of PD risks, following the definition of risk as the “effect of uncertainty on objectives” (ISO, 2009b). There are numerous examples of risks in PD that led to varying degrees of failure of the PD process and the product in the market. One of the most recent examples of PD project cost and schedule overrun is the case of the Boeing 787 Dreamliner (Tang and Zimmerman, 2009), or the large scale cost overrun of 30-40% in major PD projects for the Department of Defense (GAO, 2006). Products from the consumer industry, for example Apple’s Newton MessagePad introduced in 1993, often suffer from risks related to product quality and performance, and the associated product price (Bayus et al., 1997).

Risk management aspects are inherent in many activities that are already performed in product development. If risk management is interpreted as the structured identification and reduction of uncertainties, all PD activities that aim at reducing uncertainty can be seen as risk treatment measures. These include for example knowledge management, quality management and review processes, design automation, and early supplier or customer integration. In practice, however, these conceptually-similar activities tend to be managed as separate functions rather than an integrated approach to managing PD.

Risk management (RM) in PD is an important tool to minimize these risks in PD projects and thus increase their likelihood of success and create value. RM contributes directly to project and product success by creating transparency regarding the risk situation, thus focusing management attention and enabling them to minimize PD risks. It allows for considering both risk and return in PD projects and contributes by increasing the quality of the PD processes, one of the main determinants of product success (Cooper and Kleinschmidt, 1995). Additionally, there is an increasing pressure on organizations to execute risk management processes as part of corporate governance, risk management and compliance (GRC) activities of controlling and internal audit departments (Spira and Page, 2002). This makes it even more important for engineers and engineering managers to define and implement a value-creating PD risk management process, before the discussion is dominated by corporate functions that lack a detailed understanding of engineering processes.

4 PD Risk Management Processes

4.1 Risk Management Reference Processes

Recently, the International Organization for Standardization (ISO) released the standard ISO 31000 (ISO, 2009a), along with additional documentation regarding possible methods for the application within the process steps (ISO, 2009c), as well as a document concerned with the definition of risk management-related terms (ISO, 2009b).

The approach of the ISO 31000 is to provide a generic risk management framework that is applicable to different industries and different problem scopes. The process model consists of the following 7 main steps (also see Figure 4). The 5 "core" risk management processes of establishing the context, risk identification, analysis, evaluation and treatment are flanked by an integration process as well as a monitoring and review process.

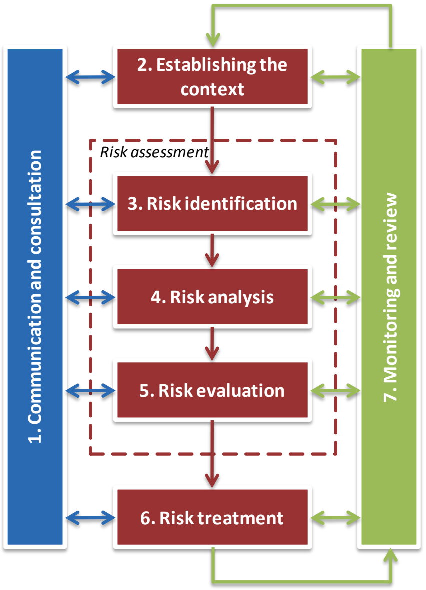


Figure 4: Risk Management Reference Process according to ISO 31000

1. Communication and consultation: Communication and consultation with external and internal stakeholders should take place during all stages of the risk management process. It should facilitate the exchange of necessary information and coordination of stakeholders and their perceptions throughout the entire risk management process.

2. Establishing the context: By establishing the context, the objectives, scope and criteria for the remaining risk management process are defined. This addresses both company external and as well as internal factors, the role of the risk management process within the company, as well as the basic criteria used to evaluate risks.

3. Risk identification: This step consists of identifying sources of risk, areas of impact, and events with their causes and consequences. The aim of the step is to create a comprehensive list of risks based on events that have a significant influence on the achievements of the objectives.

4. Risk analysis: The analysis of the risks identified previously develops a deeper understanding of these risks. It generates the necessary information for a correct evaluation of the risk (both regarding the appropriate method for evaluation, as well as the necessary data), and for the development of effective treatments.

5. Risk evaluation: During risk evaluation, based on the information gathered in the risk analysis, decisions are made regarding which risks need treatment and the priority of the risk treatments. It uses the criteria that were defined during the establishment of the context.

Steps 3-5 (risk identification, analysis and evaluation) constitute the risk assessment process.

6. Risk treatment: For every risk that needs treatment, one or more options to deal with the risk are selected and implemented. It involves assessing different treatments, assessing the resulting residual risk, and deciding whether additional risk treatments are necessary to achieve the intended risk reduction.

7. Monitoring and review: The identified risks, including the identification of emerging risks, are monitored and reviewed, so changes to their evaluation and treatment can be made if necessary. The execution of the risk management process is monitored and reviewed as well to enable process control and improvements.

4.2 Generic Process Steps for PD Risk Management

The generic risk management framework processes can be interpreted for PD risk management as illustrated in Figure 5. For a detailed review of current research and methods in PD risk management along these processes, please refer to (Oehmen et al., submitted) and see Table 1 for an overview of applicable methods.

In order to **establish the context** of the risk management process, first the PD project that is the focus of the process has to be defined. To rank and select the PD projects, they can be analyzed at a high level regarding their exposure to uncertainty, e.g. in terms of innovation content, familiarity with technologies or markets, and regarding to their importance, e.g. regarding expected market share or their planned budget. It is also important to establish a general understanding of the expected risk / return balance of the project (see Figure 3), in order to have a rough guidance for acceptable levels of risks. Delimiting the PD process scope in the next step establishes clear boundaries for the risk management process. The risk management process can either encompass the entire product design and development process, i.e. from the first idea generation to market introduction, or only parts thereof, for example the search for solution principles to certain requirements. This also informs the next step that defines possible sources of uncertainty that will be considered. These sources can for example be structured regarding the degree to which they can be influenced, e.g. sources of uncertainty from within the own company, from partner companies and the supply chain, or from environmental factors. The last process step is one of the most important: defining the PD objectives. As risk is defined as the influence of uncertainty on objectives, only after the objectives are clear, risk can be discussed. The objectives can either focus on project-level metrics, such as budget, schedule and process standard adherence, product-related metrics, such as time-to-market, performance level and product cost, or higher-level metrics, such as the net present value of the project, customer satisfaction, or market share. To be able to later understand the relationship between risks, it is advisable to already have made the relationship between the different objectives clear at this stage.

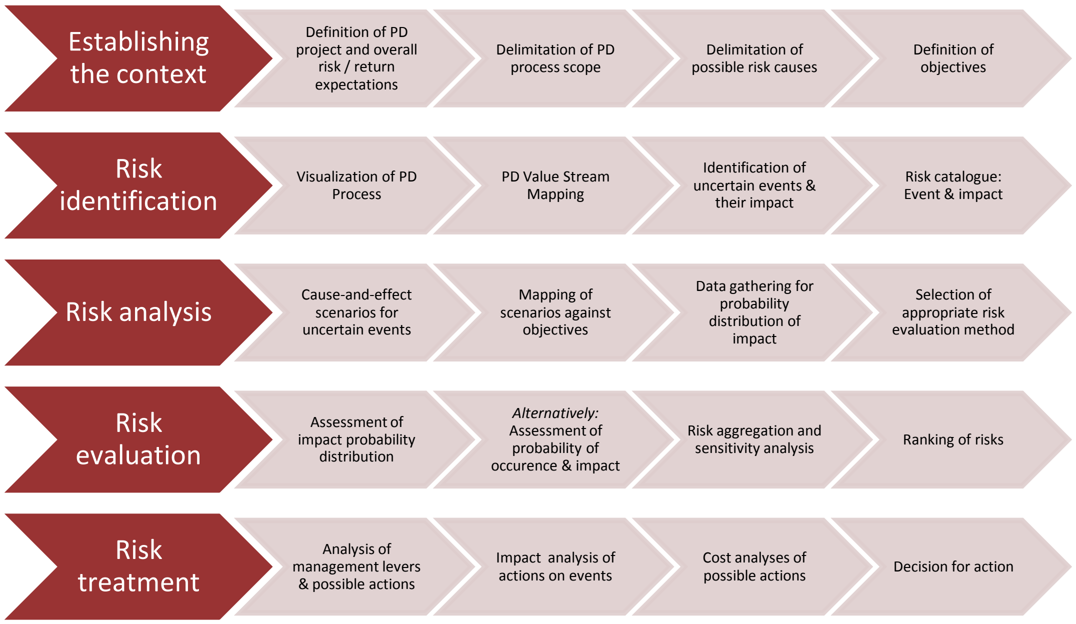


Figure 5: PDRM Reference Process for Core Process Elements

During this phase, the system boundary for the risk management process is established. It is important to note that the expectations regarding the scope of risks that should be identified, the definition of objectives, possible causes and process scope are aligned with each other. If, for example, one of the objectives is to “have more than 30% of profits coming from products not older than 3 years”, or “have a product profitability of over 15%”, the scope of the analysis must include customer requirements, supplier capabilities, as well as their continuous integration into the PD process. Correspondingly, if risk management activities are focused on achieving a high technical reliability, broader questions of risks to profitability and market share cannot be discussed.

The first step during **risk identification** is the visualization of the PD process. This visualization is based on the prior process delimitation and provides a clear and graphical representation of the PD process to all team members. This visualization is then extended to a PD value stream map (see (McManus, 2005)), which generates a better understanding of how the PD process generates value, i.e. contributes to achieving the set objectives, and what events might interfere with this. In the next step, possible uncertain events are then identified along the value stream, taking into account the prior delimitation of possible risk causes. By describing these events and their impact, a first risk catalogue can be generated.

Table 1: Overview of Risk Management Methods

Method	Reference	Establishing the context	Risk identification	Risk analysis	Risk evaluation	Risk treatment
PD project context analysis	(Ahmed et al., 2007)	X				
Structured and semi-structured interviews	(ISO, 2009c, Smith and Merritt, 2002)	X	X			
Checklists	(ISO, 2009c, Smith and Merritt, 2002)	X	X			
Brainstorming	(ISO, 2009c, Smith and Merritt, 2002)		X			
Delphi techniques	(ISO, 2009c, Browning, 1999)		X			
Process / value stream analysis	(Smith and Merritt, 2002, McManus, 2005)		X			
Quality Function Deployment	(Reich and Paz, 2008)		X	X		
Technology Readiness Scales	(Tang and Otto, 2009)		X	X	X	
Scenario analysis	(ISO, 2009c, Madachy and Valerdi, 2010, Oehmen et al., 2009)		X	X		
Root cause analysis	(ISO, 2009c)		X	X		
Structured What-if analysis	(ISO, 2009c)		X	X	X	
Fault tree analysis	(ISO, 2009c, Ahmed et al., 2007)		X	X	X	
Event tree analysis	(ISO, 2009c, Ahmed et al., 2007)		X	X	X	
Failure mode and effects analysis	(ISO, 2009c, Wagner, 2007, Segismundo and Miguel, 2008, Kmenta et al., 1999)		X	X	X	X
Cause-and-effect analysis	(ISO, 2009c, Oehmen et al., 2009)			X		
Portfolio Management	(Cooper et al., 2001, Wirthlin, 2009)			X	X	X
Monte Carlo simulation	(ISO, 2009c, Hassan et al., 2005, Blau et al., 2000)				X	
Consequence / probability matrix	(ISO, 2009c, Smith and Merritt, 2002)				X	
Risk Value Method	(Browning et al., 2002)				X	
Real Options	(Mikaelian, 2009)				X	X
Cost / benefit analysis	(ISO, 2009c, Smith and Merritt, 2002)					X
Multi-criteria decision analysis	(ISO, 2009c)					X

Building cause-and-effect scenarios from the identified uncertain events is the first step in the **risk analysis** phase. This helps to aggregate singular risks into a larger framework and thus create a deeper and better understanding of the overall situation. These aggregated scenarios may then be mapped against the objectives to assess their cumulative impact. In order to prepare the following risk evaluation phase, available data are gathered regarding the probability distribution of the impact of the events or scenarios. Depending on the amount and quality of the data, an appropriate risk evaluation method is chosen.

Based on the method chosen before, the first step during **risk evaluation** is the assessment of the impact probability distribution regarding its overall criticality (see for example the discussion of the risk value method in section 5.2). If no continuous probability distribution is used, the risk can also be assessed by quantifying a single point of probability of occurrence and impact. If the risks have not been aggregated into scenarios before, they may now be aggregated based on their assessment. Note that the criticality rating of a risk also depends on the expected risk / return balance of the PD project, as discussed during the first process step. The risks are then ranked according to their criticality, e.g. in probability / impact or risk / return portfolios, or by single-dimensional methods such as value at risk.

The last step is the **risk treatment**. It starts with an analysis of the available management levers and possible actions to influence the identified events, either reducing the probability of occurrence of negative events or influencing the probability distribution of outcomes towards positive values. The cost analysis of possible actions is part of an overall optimization of the risk / return balance of the entire PD project and reflects the target positioning of the project. The last step is the decision for a certain number of risk treatments and their implementation. It is important to note that while resource expenditures for risk treatment will likely be made in this last step, planning and establishing allowances for those expenditures will often have to be done in the earliest stages of a PD effort.

4.3 The Organizational Context

For successful risk management, not only the process itself is important, but also the corporate culture and organizational context. Similar to other efforts that aim at a continuous improvement of processes and product, risk management is dependent on the following factors:

1. Clear and shared understanding of relevance and goals of risk management: Only if all stakeholders, from senior management to junior engineers, recognize the relevance of the risk management process and agree on a matching set of goals will the process receive the necessary attention and quality execution.
2. Matching expectations, responsibilities and influence: Risk management can only be successful if the expectations or goals towards the process match with the responsibilities (or interests) of the involved people, as well as with their ability to execute relevant actions. This also includes that identified risks and proposed treatment measures are being taken seriously, and their execution is monitored.

3. Cross-boundary and cross-hierarchical process teams: To address a number of important risks that reside at organizational interfaces, both between PD and other functions within the company or partner organizations, but also between levels of hierarchy, the teams conducting risk management workshops have to represent all relevant organizations.
4. Sufficient resource allocation: Risk management does not only need resources in the form of schedule or funding contingencies, but especially resources to execute the risk management process itself properly. This includes addressing risk management knowledge in staffing decisions, allowing sufficient time for team members to participate in risk management workshops, and setting aside funds to conduct or contract detailed analyses where necessary.

5 An Overview of LAI's Research in PD Risk Management

The research conducted at LAI on risk management in product design and development can be divided into the four areas of risk management: methods and processes, the management of uncertainty in PD, the application of real options theory, and portfolio-level PD risk management (see Table 2 below). The documents are either publicly available via the LAI website (follow the download link), or can be requested at LAI.

Table 2: Overview of PD Risk Management related Research at LAI

Area / Author	Publication	Citation
Risk Management Methods and Processes		
Claudia Wagner	"Specification Risk Analysis: Avoiding Product Performance Deviations Through An FMEA-Based Method." Master's Thesis, LAI and Technical University of Munich, May 2007.	(Wagner, 2007) **Download link**
Raymond Madachy Ricardo Valerdi	"Automating Systems Engineering Risk Assessment", Proceedings of the 8th Conference on Systems Engineering Research, Hoboken, NJ, March 17-19 2010	(Madachy and Valerdi, 2010) **Download link** (slides only)
Josef Oehmen	"Approaches to Crisis Prevention in Lean Product Development by High Performance Teams and Through Risk Management." Master's Thesis, LAI and Technical University of Munich, September 2005.	(Oehmen, 2005) **Download link**
Josef Oehmen Muhammad Ben-Daya Warren Seering Mohammad Al-Salamah	"Risk Management in Product Design: Current State, Conceptual Model and Future Research," Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2010	(Oehmen et al., submitted)
Management of Uncertainty in PD		
Tyson R. Browning John J. Deyst Steven Eppinger Daniel E. Whitney	LAI Working Paper WP99-03, December 1999. Complex System Product Development: Adding Value by Creating Information and Reducing Risk; published as "Adding Value in Product Development by Creating Information and Reducing Risk," IEEE Transactions on Engineering Management, 49(4), pp. 443-458, 2002.	(Browning et al., 2002) **Download link**
Steve Bresnahan	"Understanding and Managing Uncertainty in Lean Aerospace Product Development." S.M. Thesis, System Design and Management (SDM), Engineering Systems Division, Massachusetts Institute of Technology, February 2006.	(Bresnahan, 2006) **Download link**
Hugh McManus Daniel Hastings	"A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems." IEEE Engineering Management Review, Vol. 34, No. 3, Third Quarter	(McManus and Hastings, 2005) **Download link**

Area / Author	Publication	Citation
Real Options Theory		
Tsoline Mikaelian	“An Integrated Real Options Framework for Model-based Identification and Valuation of Options under Uncertainty.” Ph.D. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, June 2009.	(Mikaelian, 2009) Download link
Portfolio-Level PD Risk Management		
Joseph R. Wirthlin Warren Seering Eric Rebentisch	“Understanding Enterprise Risk Across an Acquisition Portfolio: A Grounded Theory Approach.” Seventh National Symposium on Space Systems Engineering & Risk Management, Los Angeles, CA, February 26-29, 2008.	(Wirthlin et al., 2008) Download link
Joseph R. Wirthlin	“Identifying Enterprise Leverage Points in Defense Acquisition Program Performance." Ph.D. Thesis, Engineering Systems, Engineering Systems Division, Massachusetts Institute of Technology, September 2009.	(Wirthlin, 2009) Download link

5.1 Risk Management Methods and Processes

The introduction to PD risk management given in the sections above is founded on past LAI research in the field. (Oehmen, 2005) reviews the pre-ISO 31000 literature on PD risk management and develops a process framework similar to that introduced by ISO. The publication also contains an overview of PD-related risk management methods for every process step; together with (ISO, 2009c, Oehmen et al., submitted), it is a good starting point for an overview of current methods (also see Table 1).

(Wagner, 2007) focuses specifically on the adaptation of the well-known FMEA method to analyze and manage product design and development processes. It is applied to specification-related risks (see Figure 6).

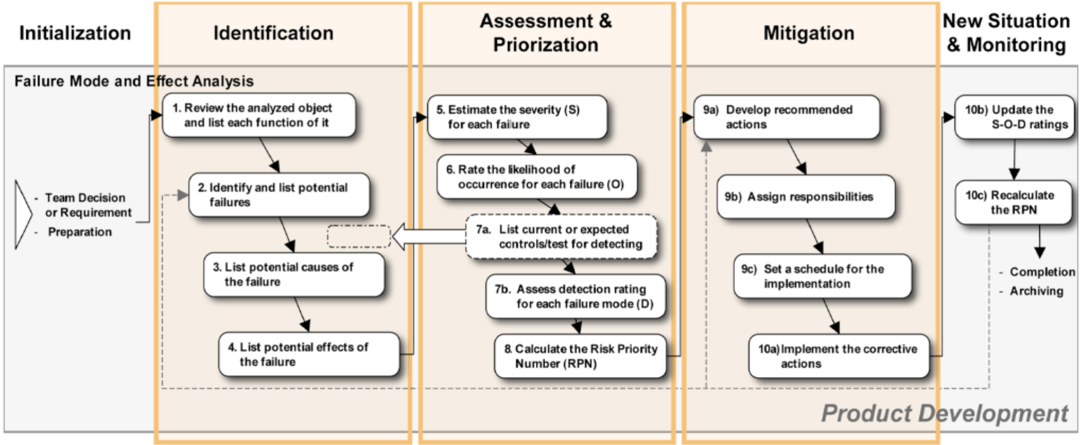
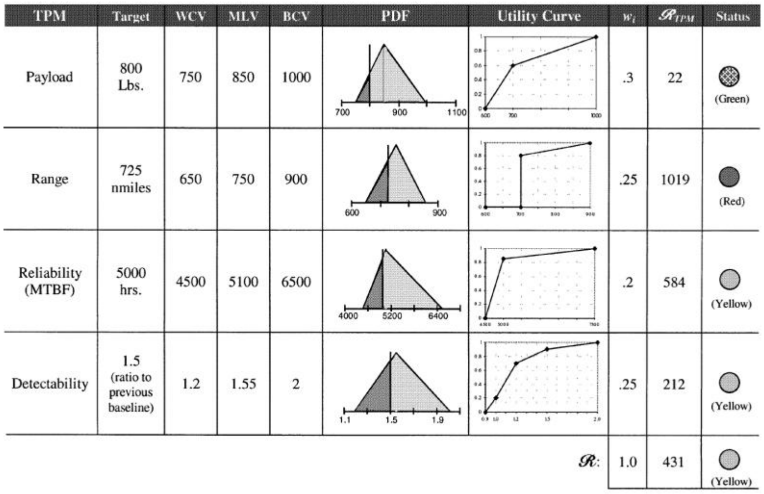


Figure 6: FMEA adapted to PD processes (Wagner, 2007)

Meeting specifications during the design phase is crucial for the later success of a product. The research analyzes the characteristics of this design phase from a risk management perspective. It develops 24 requirements for a method to manage the risk of not achieving specifications, and based on these requirements, develops a risk management tool following the FMEA process. It identifies, assesses, and ranks product specifications that are challenging to achieve. It avoids product deficiencies and provides a systematic approach to develop appropriate mitigation measures. Thus, the method seeks to prevent time and cost-consuming changes at a later point.

(Madachy and Valerdi, 2010) describes an automated expert system tool, Expert COSYSMO. It is a knowledge-based method for systems engineering risk assessment and mitigation. It is an extension of the COSYSMO cost model which supports PD project planning by identifying, categorizing, quantifying, and prioritizing system-level risks and project execution by providing mitigation advice. The knowledge base codifies the experience of seasoned systems engineering practitioners to identify and quantify risks, and provide risk mitigation advice for users to help develop their project-specific mitigation plans. This expertise is captured in an automated Internet-based tool that simultaneously estimates cost and assesses risk (the tool can be accessed at https://diana.nps.edu/MSAcq/tools/ExpertCOSYSMO.php). During estimation it helps decision makers flag risks for further analysis and mitigation, then provides the associated risk control advice. Users can update the rule base and have the opportunity to integrate it into a more comprehensive risk management framework. The tool supports common process and measurement frameworks, both as a standalone process tool and a provider of essential data for risk metrics indicators.

5.2 Management of Uncertainty in Product Development



TPM	Target	WCV	MLV	BCV	PDF	Utility Curve	w_i	$\mathscr{R}_{TPM}$	Status
Payload	800 Lbs.	750	850	1000			.3	22	● (Green)
Range	725 nmiles	650	750	900			.25	1019	● (Red)
Reliability (MTBF)	5000 hrs.	4500	5100	6500			.2	584	● (Yellow)
Detectability	1.5 (ratio to previous baseline)	1.2	1.55	2			.25	212	● (Yellow)
						$\mathscr{R}$:	1.0	431	● (Yellow)

Figure 7: Example application of the "risk value method" from (Browning et al., 2002)

(Browning et al., 2002) develops the “risk value method” to link the probability distribution of performance outcomes in PD projects with the customer utility function (also see Figure 7). Many firms expend a great amount of effort to increase the customer value of their product development processes. Yet, in PD, determining how and when value is added is problematic. The goal of a PD process is to produce a product “recipe” that satisfies requirements. Design work is done both to specify the recipe in increasing detail and to verify that it does in fact conform to requirements. As design work proceeds, certainty increases surrounding the ability of the evolving product design (including its production process) to be the final product recipe (i.e. technical performance risk decreases). The proposal is that making progress and adding customer value in PD equate with producing useful information that reduces performance risk. A method, the risk value method, is developed in this paper. It integrates current approaches such as technical performance measure tracking charts and risk reduction profiles.

(Bresnahan, 2006) explores the role of uncertainty in lean product development, demonstrates the relationship between risk mitigation activities and the generation of customer value in the design and development process, and provides guidelines for completing these activities in a manner that reduces cycle time, assures quality, and makes the most efficient use of company resources. Product development teams that undertake aggressive and rigorous activities to identify uncertainties and risk ultimately encounter fewer problems and unplanned rework. These teams complete their project at an overall lower cost than the shortsighted teams who spend less to address uncertainty and risk, but meet greater problems later in the process (refer to Table 3 for a suggestion of risk-related review criteria at the different stage gates of a PD project).

Table 3: Recommended Processes at Stage Gates for Risk Mitigation (Bresnahan, 2006)

Stage Gate	Risk-related review criteria
Stage Gate 1 – After requirements capture and prior to concept generation	• Review customer integration activities which should be complete (customer risk) • Establish plans or targets for reuse(design errors, variability), set-based design (new technology), supplier integration (enterprise capability) and/or, upgradeable architectures(life cycle concerns, interactions) for the next phase of the program
Stage Gate 2 – After concept selection and prior to preliminary design	• Review results against plans established in stage gate 1 • Establish plans or targets for prototyping (new technology, design errors, enterprise capability, customer), simulation (interactions), sensitivity analysis (variability, interactions) and/or DFX (life cycle concerns).
Stage Gate 3 – After preliminary design and prior to detailed design	• Review results against plans established in stage gate 2 • Establish plans or targets for standard work (design errors, interactions, enterprise capability), tolerance control and margin allowances (variability), design reviews (customer, life cycle)
Stage Gate 4 – After detailed design and prior to verification	• Review results against plans established in stage gate 3 • Establish plans or targets for integration test (interactions)
Stage Gate 5 – After verification and prior to certification	• Review results against plans established in stage gate 4 • All risks should be reduced adequately by this time

Acceptable levels of uncertainty that may remain at each stage of the program will be highly dependent on the nature of the product and the risk tolerance of the organization. However, in the interest of value creation, managers should expect that quantitatively or qualitatively measured risks levels should decline at a rate over time that approximates the rate of expenditures. If one believes that product development is truly about the elimination of uncertainty that the product will satisfactorily perform its required function, then substantial expenditures without concurrent reductions in the level of uncertainty could be an indicator of wasteful actions.

5.3 Application of Real Options Theory

(Mikaelian, 2009) focuses on flexibility as an important means of managing uncertainties and leverages real options analysis that provides a theoretical foundation for quantifying the value of flexibility. Complex systems and enterprises, such as those typical in the aerospace industry, are subject to uncertainties that may lead to suboptimal performance or even catastrophic failures if unmanaged. This work introduces an Integrated Real options Framework (IRF) that supports holistic decision making under uncertainty by considering a spectrum of real options across an enterprise (see Table 4 for an example of real options documentation).

Table 4: Documentation of Real Options according to the Integrated Real Options Framework (IRF) (Mikaelian, 2009)

Question	Generic Integrated Real Options Framework (IRF) answer	Example (real options in UAV swarm scenario)
Why is the real option needed?	To manage a specific uncertainty input to the IRF	To manage uncertainty in the surveillance target revisit rate requirement while maintaining communication among neighbors
What type of real option?	Identification of types of real options using the logical C-DSM	Option to deploy sparse swarm
How to enable the real option?	Identification of mechanisms using the logical C-DSM	Acquisition of homogeneous UAV swarm with long range UAV-to-UAV communication system
Where to enable the real option?	Mapping of mechanisms and types to enterprise views	Acquisition mechanism (strategy view) enables option in operations (process view)
When to enable/exercise the real option?	Valuation determines whether it is worthwhile to enable real option / option is exercised as needed when uncertainties resolve, before expiration date	Enabled upon acquisition of swarm (at 40% high revisit rate missions); deploy sparse swarm for low revisit rate missions
Who enables/exercises the real option?	Enterprise C-DSM provides the trace- ability to identify relevant stake- holder(s)	Option enabled by acquisitions department; can be exercised by UAV operators

Real options are defined as the right but not the obligation to take action in the future. For PD projects, modularity, redundancy, buffering or staging can be understood as Real Options. In the context of the IRF, enterprise architecture is described in terms of eight views and their dependencies and modeled using a coupled dependency structure matrix (C-DSM). A DSM represents relationships between objects in the form of a matrix. The objective of the IRF is to leverage the C-DSM model in order to identify and value real options for uncertainty management.

A new characterization of a real option as a mechanism and type is introduced. This characterization disambiguates among 1) patterns of mechanisms that enable flexibility and 2) types of flexibility in a system or enterprise. Second, it is shown that a classical C-DSM model cannot represent flexibility and options. The logical C-DSM model is introduced to enable the representation of flexibility by specifying logical relations among dependencies. Third, it is shown that in addition to flexibility, two new properties, optionability and realizability, are relevant to the identification and analysis of real options. Fourth, the logical C-DSM is used to estimate flexibility, optionability and realizability metrics. Methods that leverage these metrics are developed to identify mechanisms and types of real options to manage uncertainties. The options are then valued using standard real options valuation techniques. The framework is demonstrated through examples from an unmanned air vehicle (UAV) project and management of uncertainty in surveillance missions.

5.4 Portfolio-level Risk Management

Portfolio-level risk management extends project-level risk management and aggregates its outcomes – ideally – to the next higher level. Risk is one of the highest cited criteria used in PD portfolio management (see Figure 8). (Wirthlin, 2009) explores the current state of Portfolio Risk Management in PD. Although managing product portfolios through a conceptual risk measure common across the products in the portfolio is seen as very desirable, a survey showed that aggregation of risk is very rarely done and usually considered too hard to do.

But aggregation of risk is not the only way to consider risks in a portfolio. Additional evidence suggests even more kinds of risk are at play when considering portfolios. Several key reasons can be named in support of portfolio management:

- Strategic fit - forging a link between project selection and business strategy
- Financial reward - Maximize return, R&D productivity and achieve financial goals
- Risk and probability of success - balance risk and return of PD projects and portfolio
- Timing - Balance long and short term projects
- Maintain competitive position of the business – increase sales and market share
- Properly and efficiently allocate scarce resources
- Provide better objectivity for project selection
- Achieve focus – not doing too many projects, focus resources on important projects
- Better communicate priorities within the organization

Several portfolio management tools and techniques have emerged over time using traditional project financial information that may be construed to include risk as a factor. These include the Growth-share matrix (Boston or BCG matrix), the GE multi-factoral analysis (McKinsey matrix), the advantage Matrix (another BCG matrix), the Ansoff Product-Market Growth matrix and the Contribution Margin Analysis method. These matrices attempt to put different projects into different categories to simplify managing towards the benefits of portfolio management.

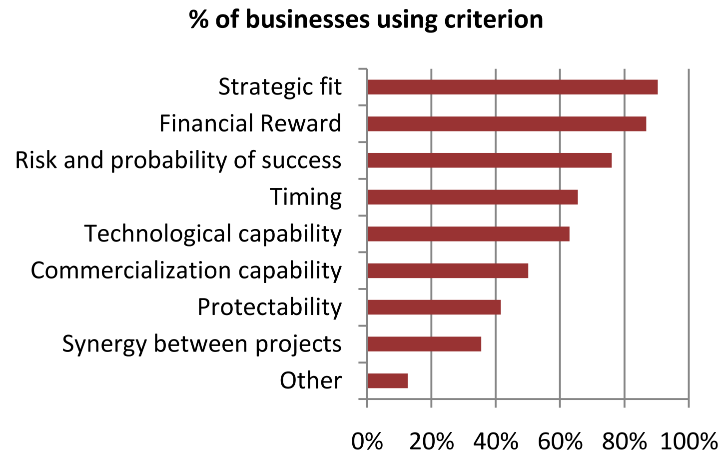


Figure 8: Criteria used in PD Portfolio Management (Cooper et al., 2001)

(Wirthlin et al., 2008) analyses the current state of the art regarding portfolio level risk management in Air Force acquisition programs. Data collected from portfolio managers working at multiple levels of the system suggest that most are unable to articulate the risk carried by their portfolio of product development activities or what this means to them. However, the same interviews suggest they strongly desire this capability. From a review of the applicable literature in the areas of risk, product development (acquisition) and product portfolio management, portfolio-level risk applications are found to be sparse and ill-conceived. The interviews identified several key themes that cut across all levels of the hierarchy. These themes are money, personnel, or requirements, or some combination of all three impacting the outcome measures of individual programs, resulting in increasing costs and/or schedule slips. While portfolio leaders are expected to live within the resources available, they have few effective levers of control to influence portfolio performance. They have little capability to prune the portfolio or to 'throttle' the execution of existing programs (e.g. speed up, slow down). But they also occasionally serve in gatekeeper functions with a great deal of responsibility – as a Source Selection Authority, Milestone Decision Authority, or to function as an Award Fee Designating Official. As a program advocate, portfolio leaders become reputation managers, lobbyists, and information conduits. Perhaps their greatest area of influence exists at the start of new programs because they carve out the initial team of personnel and resources until the official processes 'catch up' with the new program. One lever of control completely within their purview is the contractual mechanism with industry. However, also this lever is constrained by financial pressures outside the control of the portfolio leader. Consequently, the designated portfolio managers in this system were found to have very few means of control to influence the outcomes of their portfolios.

As the challenge to manage the development risk across a portfolio remains without a clear and satisfying solution today, it is still a focus of research at LAI.

6 Literature

Research publications by LAI (see Table 2) are available on our website at http://lean.mit.edu or can be requested at LAI.

AHMED, A., KAYIS, B. & AMORNSAWADWATANA, S. (2007) A review of techniques for risk management in projects. *Benchmarking: An International Journal,* 14**,** 22-36.

BAYUS, B. L., JAIN, S. & RAO, A. G. (1997) Too Little, Too Early: Introduction Timing and New Product Performance in the Personal Digital Assistant Industry *Journal of Marketing Research,* 34**,** 50-63.

BLAU, G., MEHTA, B., BOSE, S., PEKNY, J., SINCLAIR, G., KEUNKER, K. & BUNCH, P. (2000) Risk management in the development of new products in highly regulated industries. *Computers and Chemical Engineering,* 24**,** 659-664.

BRESNAHAN, S. M. (2006) Understanding and Managing Uncertainty in Lean Aerospace Product Development. *Master's Thesis.* Cambridge, Massachusetts Institute of Technology.

BROWNING, T. R. (1999) Sources of Schedule Risk in Complex System Development. *Systems Engineering,* 2**,** 129-142.

BROWNING, T. R., DEYST, J. J., EPPINGER, S. D. & DANIEL E. WHITNEY (2002) Adding Value in Product Development by Creating Information and Reducing Risk. *IEEE Transactions on Engineering Management,* 49**,** 443-458.

COOPER, R. G., EDGETT, S. J. & KLEINSCHMIDT, E. J. (2001) Portfolio management for new product development: results of an industry practices study. *R&D Management,* 31**,** 361-380.

COOPER, R. G. & KLEINSCHMIDT, E. J. (1995) Benchmarking the Firm's Critical Success Factors in New Product Development. *Journal of Product Innovation Management,* 12**,** 374-391.

GAO (2006) *Defense Acquisitions - Major Weapon Systems Continue to Experience Cost and Schedule Problems under DOD's Revised Policy (GAO-06-368),* Washington, United States Government Accountability Office, Report to Congressional Committees.

HASSAN, R., NEUFVILLE, R. D., WECK, O. D., HASTINGS, D. & MCKINNON, D. (2005) Value-at-Risk Analysis for Real Options in Complex Engineered Systems. *IEEE International Conference on Systems, Man and Cybernetics.*

ISO (2009a) *ISO 31000:2009(E) - Risk management - Principles and guidelines,* Geneva, International Organization for Standardization.

ISO (2009b) *ISO Guide 73:2009 - Risk management - Vocabulary,* Geneva, International Organization for Standardization.

ISO (2009c) *ISO/IEC 31010: Risk management - Risk assessment techniques,* Geneva, International Organization for Standardization & International Electrotechnical Commission.

KMENTA, S., FITCH, P. & ISHII, K. (1999) Advanced Failure Modes and Effects Analysis of Complex Processes. *Proceedings of the 1999 ASME Design Engineering Technical Conferences, September 12-15, 1999, Las Vegas, Nevada***,** 1-9.

MADACHY, R. & VALERDI, R. (2010) Automating Systems Engineering Risk Assessment. *Proceedings of the 8th Conference on Systems Engineering Research, Hoboken, NJ, March 17-19 2010*.

MCMANUS, H. (2005) *Product Development Value Stream Mapping (PDVSM) Manual,* Cambridge, MA, Lean Advancement Initiative (LAI) at MIT.

MCMANUS, H. & HASTINGS, D. (2005) A Framework for Understanding Uncertainty and it sMitigation and Exploitation in Complex Systems. *Fifteenth Annual International Symposium of the International Council on Systems Engineering (INCOSE), 10 July to 15 July 2005, Rochester, NY*.

MIKAELIAN, T. (2009) An Integrated Real Options Framework for Model-based Identification and Valuation of Options under Uncertainty. Cambridge, Massachusetts Institute of Technology.

OEHMEN, J. (2005) Approaches to Crisis Prevention in Lean Product Development by High Performance Teams and through Risk Management. Munich and Cambridge, Technical University of Munich and LAI.

OEHMEN, J., BEN-DAYA, M., SEERING, W. & AL-SALAMAH, M. (submitted) Risk Management in Product Design: Current State, Conceptual Model and Future Research. *Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2010*

OEHMEN, J., ZIEGENBEIN, A., ALARD, R. & SCHÖNSLEBEN, P. (2009) System-oriented Supply Chain Risk Management. *Production Planning & Control,* 20**,** 343-361.

REICH, Y. & PAZ, A. (2008) Managing product quality, risk, and resources through resource quality function deployment. *Journal of Engineering Design,* 19**,** 249-267.

SEGISMUNDO, A. & MIGUEL, P. A. C. (2008) Failure mode and effects analysis (FMEA) in the context of risk management in new product development - A case study in an automotive company. *International Journal of Quality & Reliability Management,* 25**,** 899-912.

SMITH, P. G. & MERRITT, G. M. (2002) *Proactive Risk Management - Controlling Uncertainty in Product Development,* New York, Productivity Press.

SPIRA, L. F. & PAGE, M. (2002) Risk Management - The reinvention of internal control and the changing role of internal audit. *Accounting, Auditing & Accountability Journal,* 16**,** 640-661.

TANG, C. S. & ZIMMERMAN, J. D. (2009) Managing New Product Development and Supply Chain Risks: The Boeing 787 Case. *Supply Chain Forum: An International Journal,* 10**,** 74-85.

TANG, V. & OTTO, K. N. (2009) Multifunctional Enterprise Readiness: Beyond the Policy of Build-Test-Fix Cyclic Rework. *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Design Theory and Design IDETC/DTM 2009 , August 30 - September 2, 2009, San Diego, California***,** 1-9.

ULRICH, K. T. & EPPINGER, S. D. (1995) *Product design and development,* New York, McGraw-Hill.

WAGNER, C. (2007) Specification Risk Analysis: Avoiding Product Performance Deviations through an FMEA-based Method. Munich and Cambridge, Technical University of Munich and LAI.

WIRTHLIN, J. R. (2009) Identifying Enterprise Leverage Points in Defense Acquisition Program Performance. *Ph.D. Thesis, Engineering Systems, Engineering Systems Division, Massachusetts Institute of Technology, September 2009*.

WIRTHLIN, J. R., SEERING, W. & REBENTISCH, E. (2008) Understanding Enterprise Risk Across an Acquisition Portfolio: A Grounded Theory Approach. *Seventh National Symposium on Space Systems Engineering & Risk Management, Los Angeles, CA, February 26-29, 2008*.