Chapter 1

Developing a Taxonomy for Risks in Product Design and Development

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1.1 Introduction

It is generally acknowledged that risks and their (mis-)management play a very significant role in the management of large-scale design, product development and engineering programs. When reviewing struggling or failed programs, “risks” are generally cited as one of the main reasons for those troubles (GAO, 2006; Oehmen *et al.*, 2012).

However, there exists no clear framework to discuss and describe these risks, as well as no quantified overview of the significance of different types of risks.

This paper makes a contribution to both areas: It begins with a literature review and discussion on risk definitions that apply to engineering programs, as well as an overview of existing taxonomies. Then, a comprehensive framework for describing engineering program risks is developed. It is based on the definition of risk as the effect of uncertainty on objectives (ISO, 2009), as well as the assumption that the overall objective of engineering programs is to deliver stakeholder value (Murman *et al*., 2002). This framework is then applied to develop a taxonomy of engineering program risks. The main elements of the taxonomy are the distinction between uncertainties that primarily affect stakeholder needs, thus leading to the “risk of wrong objectives”, as well as uncertainties affecting the engineering program execution, creating “risk of missing objectives”.

In the following part of this paper, a number of those risks are prioritised based on the results of an industry survey. The main risks that are identified are related to customer requirements stability and clarity, as well as suppliers of designs and components.

The paper concludes with a discussion of the contributions and limitations of this paper.

1.2 Overview of Definitions of Risk

Risk is both an every-day as well as a technical term. Colloquially, risk refers to the possibility of a loss (Merriam-Webster, 2014). Table 1.1 summarises a number of risk definitions that apply to product design and development:

Table 1.1. Overview of definitions of risk

Source of definition	**Definition of risk**
(Kaplan and Garrick, 1981)	Risk is the triplet of (causal) scenario, likelihood and consequence.
(Dezfuli *et al*., 2010)	Risk is the potential for performance shortfalls, which may be realised in the future, with respect to achieving explicitly, established and stated performance requirements.
(Smith and Merritt, 2002)	Risks are defined a simple cause-and-effect chains of events.
(Oehmen *et al*., 2009)	Risks are defined within complex and dynamic causal networks.
(DoD, 2006)	Risk is a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule and performance constraints.
(PMI, 2008)	Risk is an uncertain event or condition that, if it occurs, has an effect on at least one project objective: scope, schedule, cost, and quality
(INCOSE, 2007)	Risk is a measure of the uncertainty of attaining a goal, objective, or requirement pertaining to technical performance, cost, and schedule
(ISO, 2009)	Risk is the effect of uncertainty on objectives.

For the purpose of this paper, we adapt the broadest definition (ISO, 2009) to our particular application, as all other definitions can be seen as subsets thereof. Risk in engineering programs is defined as the effect of uncertainties on understanding and delivering stakeholder value.

While other papers focus on the quantification of risks (see for example Kaplan and Garrick, 1981), this paper focuses on developing a taxonomy that allows risk- and program management professionals to capture, analyse and manage risks in a structured fashion.

1.3 Review of Risk Taxonomies in Engineering Programs

A number of structures to collect and describe risks in engineering programs have been put forward and are summarised in Table 1.2. Many standards do not explicitly develop a risk taxonomy, but list types of risks instead:

Table 1.2. Overview of risk taxonomies

Source	**Types of risks / Summary of risk taxonomy**
	Types of risks
(Dezfuli *et al.*, 2010)	Types of risk: safety, technical, cost, and schedule.
(DoD, 2006)	Types of risk: threat, requirements, technical baseline, test and evaluation, modelling and simulation, technology, logistics, production, facilities, concurrency, industrial capabilities, cost, management, schedule, external factors, budget, and earned value management system.
(PMI, 2008)	Types of risk: technical, external, organisational, and project management with their subcategories.
(INCOSE, 2007)	Types of risk: technical, cost, schedule and programmatic, and supportability.
(ISO, 2009)	No specific types or risk taxonomy, as the standard is generic.
(Jiang and Klein, 2000)	Types of risks: various, most significant: lack of expertise, intensity of conflicts, lack of clarity in role definition.
(Tiwana and Keil, 2006)	Types of risks: 1. related technical knowledge; 2. customer involvement; 3. requirements volatility; 4. development methodology fit; 5. formal project management practices; 6. project complexity.
(Sicotte and Bourgault, 2008)	Types of uncertainty: technical and project uncertainty, market uncertainty, fuzziness and complexity
(Keizer *et al.*, 2005)	Types of risks: 1. Commercial viability risks, 2. Competitor risks. 3. Consumer acceptance and marketing risks, 4. Public acceptance risks, 5. Intellectual property risks, 6. Manufacturing technology risks, 7. Organisation and Project management risks, 8. Product family and brand positioning risks, 9. Product technology risks, 10. Screening and appraisal risks, 11. Supply chain and sourcing risks, 12. Trade customer risks.
	Taxonomies
(Yeo and Ren, 2008)	Taxonomy: Project management processes; organisational context; technical content; environment.
(Persson *et al.*, 2009)	Taxonomy: Task, structure, actor, technology.
(Lyytinen *et al.*, 1998)	Taxonomy: Task, actor, structure, technology and their relationship.

The review of the literature clearly shows that there is no clear taxonomy currently available to describe risks in engineering programs in a structured fashion. Existing “taxonomies” are not linked to clear definitions of risks, and most literature sources only present (semi)-structured collections of risks that are neither mutually exclusive nor cumulatively exhaustive.

1.4 Developing a Taxonomy for Engineering Program Risks

For developing a risk taxonomy, we start with the definition of risk as the effect of uncertainty on objectives (see Section 1.2). That leads to the three obvious question: What objectives? What uncertainties? And: What effects?

1.4.1 Objectives of Engineering Programs

While the discussion of the “right objectives” of engineering programs and product development would probably easily fill a book, for our purpose we define the overall objective of product development in the most general terms as generating value for the engineering program stakeholders (Murman *et al*., 2002).

Value itself can be interpreted in a number of ways, for example as profitable products, cost effectiveness production systems and usable knowledge (Ward, 2007), willingness to pay (Mascitelli, 2006), as the quotient of benefit and cost (Welo, 2011), as the generation of information and reduction of uncertainty (Browning *et al.,* 2002) or as an aggregated function of importance of need, degree of need fulfilment, timeliness and cost (Slack, 1998). For building the risk taxonomy, we define generating value (*i.e.* the overall objective of engineering programs) as fulfilling stakeholder needs (Norman and Draper, 1986; Griffin and Hauser, 1993; Ulrich and Eppinger, 1995).

To operationalize this definition (also see Figure 1.1), we decompose program outcomes into distinct categories in such a way that allows us to describe all relevant programs outcomes in a structured fashion where the different categories are a mutually exclusive and cumulatively exhaustive.

Based on this structure, all relevant engineering program outcomes are captured. In our example, the two top-level categories are program execution attributes (*e.g.* program schedule, program cost), and artefact attributes (*i.e.* attributes of the artefact that is generated by the program (system, product, process, service), such as total weight or technical performance attributes.

Parallel to the concrete engineering program outcomes, the needs of all stakeholders, *i.e.* their preferences, regarding all possible outcomes have to be captured. In our example, we use utility functions (Fishburn, 1970) to describe those preferences and their dependencies.

The overall objective of the engineering program is to maximise the program value, *i.e.* maximise the utility of the program across all stakeholders considering all program outcomes.

This also includes cost or other “negative” attributes (for example total weight), where the utility is inversely related to the realised outcome.

Fundamentally, the model of engineering program objectives is not sensitive towards the particular decomposition that is used to describe program outcomes, or the method used to capture stakeholder needs, as long as consistency is maintained between capturing stakeholder needs and the corresponding outcomes that are achieved by the program.

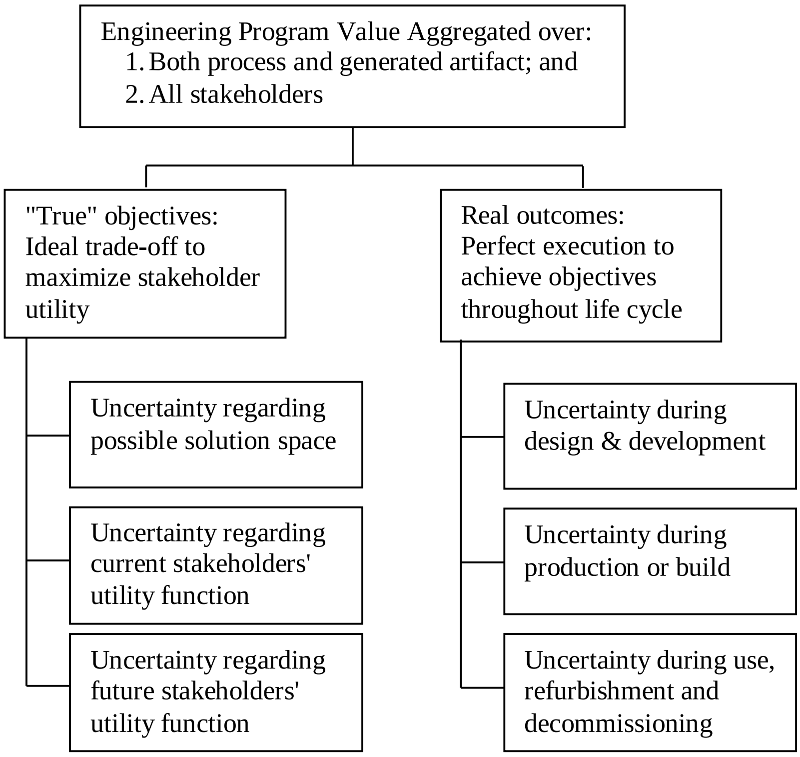

Figure 1.1. The achievement of engineering program value is defined by stakeholder needs and corresponding program outcomes

1.4.2 Uncertainties in Engineering Programs

Given the structure of engineering program objectives introduced above, uncertainties can affect the objectives through two fundamental pathways: By affecting stakeholder needs and/or by affecting the program outcomes. As discussed above, uncertainties (and depending on the definition of objectives, risks) are linked in complex causal networks. These possible interrelationships are not discussed here. Table 1.3 provides a preliminary list of uncertainties in PD programs, taken from the literature summarized in Table 1.2, as well as interactions with an industry focus group. It is broken down by the two pathways, as well as the top-level decomposition of engineering program outcomes (program execution attributes and artefact attributes).

Table 1.3. Examples of uncertainties

Categories of program outcomes objectives:	**Uncertainties affecting definition of stakeholder needs regarding…**	**Uncertainties affecting achievement of program outcome regarding…**
Engineering Program Execution Attributes **(*e.g.* process and organisation quality, execution cost and resource needs, execution lead time)**	• Completeness of program requirements • Stability of existing program requirements • Program execution performance of competition • Quality and frequency of customer interaction • Effectiveness of contracting practices • Quality and accuracy of plans and estimates (*e.g.* regarding cost and schedule)	• Stability of program execution • Organisational integration of the extended enterprise • Overall effectiveness of processes • Roles and responsibilities within the program • Alignment of competency and culture • Integration and effectiveness of process metrics and KPIs
Artefact Attributes **(*e.g.* technical performance, lifecycle cost, availability)**	• Completeness of artefact requirements • Stability of existing artefact requirements • Performance of competing artefacts (*e.g.* competitor product) • Market trends • Quality and accuracy of technical performance estimates (*e.g.* trade-off studies)	• Supplier engineering quality • Effective performance of technology • Effective performance of system after integration

1.4.3 Effects of Uncertainties on Objectives in Engineering Programs

Based on above discussion, uncertainties have a two-fold effect on objectives: First, they affect the quality of the objectives themselves (*i.e.* how well the objectives represent the true stakeholder needs). Second, they affect the quality with which an engineering program achieves those objectives.

In some sources, both "upside risks" (or opportunities) and "downside risks" (*i.e.* risks leading to a decreased overall value) are discussed. The implications for engineering programs are summarised in Table 1.4:

Table 1.4. Categories of uncertainty effects

	Uncertainties affecting definition of stakeholder needs	**Uncertainties affecting achievement of program outcome**
Uncertainty leading to "downside risk"	• System of objectives of program are below overall optimum trade-off value for all stakeholders over the lifecycle of the program	• Actual overall program outcomes fall short of objectives
Uncertainty leading to "upside risk"	• System of objectives of program are below overall optimum trade-off value for all stakeholders over the lifecycle of the program, but happen to align with unanticipated future configuration of stakeholder value	• Actual overall program outcomes exceed objectives

The "downside risks" are uncontroversial - not properly representing stakeholder needs or not achieving the set objectives diminish the actual value that is generated.

Regarding the concept of "upside risks", a "double negative" case is theoretically possible, but probably of mostly of academic interest: The stakeholder needs are not captured properly and subsequently the objectives do not represent the true stakeholder needs. Then the program fails to achieve these objectives, instead delivering results that are closer to the true stakeholder needs that were never properly understood, thus generating more value than initially anticipated. Whether or not the cases of exceeding stakeholder needs and objectives represent a true upside potential is debatable (although it certainly generates more value than falling short). If the objectives exceed the true stakeholder needs, then subsequent trade-off studies did not yield the optimum result. Similarly, if specifications or objectives are exceeded - assuming the objectives were correct - effort was wasted as the results of the program randomly exceeding the objectives, and not achieving the overall balanced optimum.

In some definitions of risk and uncertainty, value is defined as the absence of uncertainty (Browning *et al.*, 2002). In our definition of uncertainty, this would translate into one of the objectives regarding the program execution being a high level of certainty regarding the achievement of the set objectives - or a high level of certainty regarding accurately capturing stakeholder needs and properly translating them into objectives for that matter. In this case, every uncertainty is a "downside risk", as it diminishes the overall value of the program.

1.5 Examples of Prioritised Engineering Program Risks

The following section explores the relative importance of a number of risks in 8 categories, which are summarized in Table 1.5 according to the taxonomy shown in Table 1.3.

Through a survey instrument, data was collected regarding the frequency and impact of a number of example engineering program risks (see Table 1.5). A total of 49 underlying risk factors were explored in the survey, and the results aggregated to the 8 risk categories shown in Table 1.5 below (additional detail can be found in Bassler (2011). The respondents were asked to respond to the survey based on their experience in the last completed engineering program. Occurrence was indicated through a yes/no/no answer question, and the frequency computed based on the overall valid responses. The impact was indicated on a verbalised 1-5 Likert scale ranging from “very low impact (the risk occurred, but could be dealt with in the routine workflow)” to “very high impact (the risk significantly threatened the overall program success)”.

Table 1.5. Example risk categories along taxonomy

	Uncertainties affecting definition of stakeholder needs	**Uncertainties affecting achievement of program outcome**
Engineering program execution attributes		• Company-internal risks: Uncertainty regarding the efficiency and effectiveness of the program processes and their execution, including skill levels and productivity of the workforce. • Supply chain risks: Uncertainty regarding component development and delivery by lower-tier organisations. • Market risks: Macroeconomic uncertainty, such as political, social environmental or economic developments • Competition risks: Uncertainty regarding the actions of competitors.
Artefact attributes	• Customer requirements understanding related risks: Uncertainty regarding the quality of understanding of the requirements by the program organisation. • Customer requirements stability related risks: Uncertainty regarding the stability of customer requirements.	• New technology risks: Uncertainty of technology maturity and performance under field conditions • System integration risks: Uncertainty of system integration readiness under field conditions

The questions were developed based on a literature review of engineering program risks, as well as through discussions with an industry focus group consisting of representatives from the risk management functions of four US aerospace and defence companies, as well as one consultancy focused on risk management in aerospace programs. The collection of risks was refined over several iterations through telephone conference calls.

Respondents were invited from the risk management organisations of six US aerospace and defence companies as part of a risk management benchmarking study. The surveys were distributed through the risk management organisation to risk management and engineering program management professionals.

The results are summarised in Figures 1.2 and 1.3.

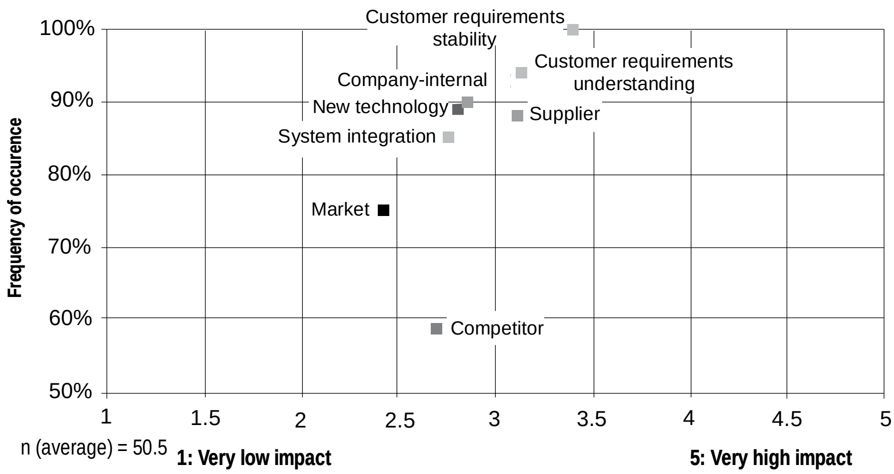

Figure 1.2. Distribution of engineering program risks regarding frequency of occurrence and severity of impact

The highest overall severity is carried by the two requirements-related risks (see also Stockstrom and Herstatt, 2008), followed by the supplier-related risks. All three risks are dominated by external factors that can only be indirectly addressed by the engineering organisations (for example through improved customer and supplier integration).

Technical risks (relating to technology and system integration) as well as risks relating to company-internal processes are in the middle of the severity range. The two lowest scoring risks are competition and market related risks, which might be specific to the aerospace and defence industry.

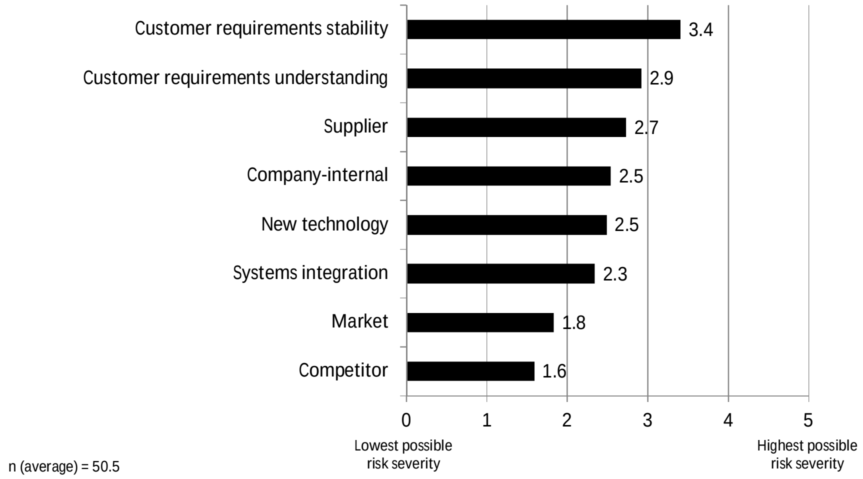

Figure 1.3. Overall severity of different engineering program risks, computed as the product of impact and frequency

1.6 Discussion and Conclusions

This paper contributes to the current state of knowledge by introducing a taxonomy for describing risks in engineering programs, covering the categories of uncertainties, effects and objectives that are necessary to describe those risks. It also contains examples of quantified engineering program risks, indicating that external risks with a root cause in customer and suppliers are most critical.

The paper makes a contribution to the academic discussion of risk management in product design and development by providing a structured framework in which to discuss risks, hopefully contributing to the clarity of the discussion.

It also makes a contribution to risk management in industrial practice by providing a structure for identifying, discussing and documenting engineering program risks.

There are several significant limitations to this paper, including: The framework has not yet been implemented in industrial practice, so feedback regarding its usability is missing. Also, the empirical data reported here is strongly biased towards engineering programs in the context of the Aerospace and Defence industry, as well as risk management professionals evaluating programs from an “ex-post” perspective. The quantified examples might therefore not be indicative of engineering risks in other industries or early phases of engineering programs.

1.7 Acknowledgements

The authors gratefully acknowledge support by the King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia, through the Center for Clean Water and Clean Energy at MIT and KFUPM under project R11-DMN-09, and the TÜV Süd Stiftung.

1.8 References

Bassler D (2011) Risk-driven design - Integrating risk management as an intrinsic part of product development. Master Thesis, Massachusetts Institute of Technology, Cambridge, MA, US

Browning TR, Deyst JJ, Eppinger SD, Whitney DE (2002) Adding value in product development by creating information and reducing risk. IEEE Transactions on Engineering Management, 49(4): 443-458

Dezfuli H, Stamatelatos M, Maggio G, Everett C, Youngblood R (2010) Risk-informed decision making. NASA/SP-2010-576. Office of Safety and Mission Assurance, NASA Headquarters, Washington DC, US

DoD (2006) Risk management guide for DoD acquisition, 6th edn. United States Department of Defense, Office of the Secretary of Defense, Washington DC, US

Fishburn PC (1970) Utility theory for decision making. John Wiley & Sons Inc, New York, NY, US

GAO (2006) Defense acquisitions - Major weapon systems continue to experience cost and schedule problems under DOD's revised policy. GAO 06-368. United States Government Accountability Office, Washington DC, US

Griffin A, Hauser JR (1993) The voice of the customer. Marketing Science, 12(1): 1-27

INCOSE (2007) Systems engineering handbook v3.1. International Council on System Engineering, Seattle, WA, US

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

Jiang J, Klein G (2000) Software development risks to project effectiveness. Journal of Systems and Software, 52(1): 3-10

Kaplan S, Garrick BJ (1981) On the quantitative definition of risk. Risk Analysis, 1(1): 11-27

Keizer JA, Vos J-P, Halman JIM (2005) Risks in new product development: Devising a reference tool. R&D Management, 35(3): 297-309

Lyytinen K, Mathiassen L, Ropponen J (1998) Attention shaping and software risk - A categorical analysis of four classical risk management approaches. Information Systems Research, 9(3): 233-255

Mascitelli R (2006) The Lean product development guidebook: Everything your design team needs to improve efficiency and slash time to market. Technology Perspectives, Northridge, CA, US

Merriam-Webster (2014) Risk. Available at: www.merriam-webster.com/dictionary/risk (Accessed on 31 January 2014)

Murman E, Allen T, Bozdogan K, Cutcher-Gershenfeld J, McManus H, Nightingale D *et al.* (2002) Lean enterprise value: Insights from MIT's Lean Aerospace initiative. Palgrave, New York, NY, US

Norman DA, Draper SW (1986) User centered system design: New perspectives on human-computer interaction. Lawrence Erlbaum Associates Inc, Hillside, NJ, US

Oehmen J, Oppenheim BW, Secor D, Norman E, Rebentisch E *et al.* (2012) The guide to lean enablers for managing engineering programs, Version 1. Joint MIT-PMI-INCOSE Community of Practice on Lean in Program Management, Cambridge, MA, US Available at: http://hdl.handle.net/1721.1/70495 Accessed on 31 January 2014

Oehmen J, Ziegenbein A, Alard R, Schönsleben P (2009) System-oriented supply chain risk management. Production Planning and Control, 20(4): 343-361

PMI (2008) A guide to the project management body of knowledge (PMBOK guide), 4th edn. Project Management Institute, Drexel Hill, PA, US

Persson JS, Mathiassen L, Boeg J, Stenskrog Madsen T, Steinson F (2009) Managing risks in distributed software projects: An integrative framework. IEEE Transactions on Engineering Management, 56(3): 508-532

Sicotte H, Bourgault M (2008) Dimensions of uncertainty and their moderating effect on new product development project performance. R&D Management, 38(5): 468-479

Slack RA (1998) The application of Lean principles to the military aerospace product development. Master Thesis, LAI and Massachusetts Institute of Technology, Cambridge, MA, US

Smith PG, Merritt GM (2002) Proactive risk management - Controlling uncertainty in product development. Productivity Press, New York, NY, US

Stockstrom C, Herstatt C (2008) Planning and uncertainty in new product development. R&D Management, 38(5): 480-490

Tiwana A, Keil M (2006) Functionality risk in information systems development: An empirical investigation. IEEE Transactions on Engineering Management, 53(3): 412-425

Ulrich KT, Eppinger SD (1995) Product design and development. McGraw-Hill, New York, NY, US

Ward AC (2007) Lean product and process development. Lean Enterprise Institute, Cambridge, MA, US

Welo T (2011) On the application of Lean principles in product development: A commentary on models and practices. International Journal of Product Development, 13(4): 316-343

Yeo KT, Ren Y (2008) Risk management capability maturity model for complex product systems (CoPS) projects. Systems Engineering, 12(4): 275-294