Doctoral theses at NTNU, 2021:405

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Managing unplanned design iterations in new product development

An approach using risk management, resilience, and organizational learning

Doctoral thesis

Norwegian University of Science and Technology
Thesis for the Degree of Philosophiae Doctor
Faculty of Engineering
Department of Mechanical and Industrial Engineering
DTU Management, Innovation division, Engineering Systems Design, Technical University of Denmark

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Preface

This thesis has been submitted to the Department of Mechanical and Industrial Engineering, the Norwegian University of Science and Technology (NTNU), and the DTU Management, the Engineering Systems Design group at the Technical University of Denmark (DTU) in partial fulfillment of the requirements for a double doctorate from both universities. The research work has been carried out at NTNU, Trondheim, and DTU, Copenhagen.

The PhD project began on September 13th, 2017 and was completed on September 29th, 2021. The work was supervised by Professor Dr. Torgeir Welo (NTNU) and Associate Professor Dr. Josef Oehmen (DTU). This project was funded by the VALUE program under the Research Council of Norway and NAPIC (NTNU Aluminium Product Innovation Centre).

This multidisciplinary research work is intended for both researchers within engineering design science, resilience, risk management, and organizational learning and practitioners designing and managing new product development projects and programs in industrial companies.

This thesis is a paper-based thesis, which means that the thesis's core consists of a series of research papers published or submitted to peer-reviewed international journals and conferences. This thesis consists of the introduction (*kappe*) and the appendix to present the research work. First, the introduction consists of several subsections to provide an overview and summary of the PhD research work. The second part consists of research papers published or submitted to peer-reviewed international journals and conferences. The appended papers are reproduced in the pre-print versions. American English is used as default style in introductory overview (Part I) of the thesis.

Trondheim, September 2021

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Like any project, this thesis is a team effort, and I would like to acknowledge the other members of the PhD project. In this regard, I would like to thank several people to whom I am very grateful.

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Thanks to my loved family and my friends for being there for me during the study period. And finally, special thanks to my wife Rabia and children (Sarah and Abiha) for their support and patience.

– Thank you all!

Abstract

Most new-product development (NPD) engineering projects encounter uncertainties from rapidly shifting market demands and developing technologies resulting in requirements change and the organization's ability to implement state-of-the-art processes reliably. This complexity triggers unplanned design iterations in the engineering design phase of the NPD process. These unplanned design iterations can be assumed to be the occurrence of a specific class of NPD project risks. Unplanned design iterations ultimately cause failures in reaching cost, schedule, quality, and customer satisfaction targets.

Today's organizations utilize traditional risk management practices to mitigate risks in NPD projects. However, even with mitigation actions in place, projects still struggle to manage NPD project risks. This thesis explores the utilization of risk management, resilience, and organizational learning in managing unplanned design iterations risk in the design and development of new products.

To achieve this aim, we employed a deductive research approach. We used different research methods in the deductive research approach, including literature review, case study, cross-sectional interviews, and survey.

First, we used a literature review to identify learning methods and conceptualize the "cost-of-learning" from failures and mistakes in the engineering design phase. In the literature review, we classified the learning methods into formal and informal learning methods. The formal learning methods involve prototyping, outsourcing, learning by doing, consulting past product reviews, and learning by training and lectures. On the other hand, informal learning method identified was learning from incidents in the design phase.

Second, we conducted an interview-based case study to evaluate the hypothesis that resilience-based "monitor-and-react" and risk management-based "predict-and-plan" approaches complement each other in managing NPD project risks. The results confirmed that resilience-based and risk management-based approaches complement each other as a strategy in managing known and unknown risks in NPD projects. Furthermore, subsequent analysis of the interviews conducted in two different companies also confirmed findings from the case company. Thus, for better avoiding and mitigating the impact of known and unknown NPD projects risks, the analysis of the empirical data suggested the overlap of risk management-based "predict- and-plan" and resilience-based "monitor-and-react" approaches.

Third, we conducted cross-sectional interviews in eight Danish companies to explore the management of unplanned design iterations, using proactive risk management (PRM) and reactive fast learning (RLF) approaches. The results of the empirical data analysis indicated that the PRM approach contributed to reducing the likelihood of unplanned design iterations. This empirical data analysis also revealed that the PRM approach is more established than the RFL approach in managing unplanned design iterations. When utilizing the RFL approach, the engineering design teams lacked a structured approach for selecting the most suitable learning methods to manage unplanned design iterations after their occurrence. In addition, when employing the RFL approach, organizations failed to convert the new process and technical knowledge (acquired during the resolution of unplanned design iterations) into organizational learning. These findings indicate that it is essential to consider the most efficient learning methods according to the types of unplanned design iterations.

Fourth, we analyzed survey data from six US-based aerospace and defense organizations using statistical methods to investigate the role of risk mitigation actions in managing NPD projects risks. The data analysis revealed that all the identified risk mitigation actions in survey data mainly contributed to mitigating different types of all NPD project risks, despite their type or categorization. The findings also revealed that organizations employed multiple risk mitigation actions to treat NPD project risks. Surprisingly, the survey data analysis uncovered that the NPD projects, using different NPD methods (waterfall, agile, or both), did not show significant differences in how they engage the risk mitigation actions.

Overall, to manage unplanned design iterations, risk management processes must be tailored according to the contextual factors of the NPD projects. For treating known and unknown NPD project risks that may cause unplanned design iterations, the overlap of risk management-based and resilience-based approaches is required. Finally, the thesis's findings recommend developing a structured approach for selecting suitable learning methods for managing unplanned design iterations after their occurrence.

List of Abbreviations

A	Applicable
DRM	Design research methodology
HAZOP	Hazard and operability studies
IEC	The international electrotechnical commission
ISO	The international organization for standardization
NPD	New product development process
NA	Not applicable
PD	Product development
PRM	Proactive risk management
PMI	Project management institute
RFL	Reactive fast learning
RQ	Research Question
SA	Strongly applicable

List of Papers

Research Paper A:

The Cost of Learning from Failures and Mistakes in Product Design: Reviewing the Literature

Shafqat, A., Oehmen, J., Welo, T. and Willumsen, P., 2019, July. The cost of learning from failures and mistakes in product design: Reviewing the literature. In *Proceedings of the Design Society: International Conference on Engineering Design* (Vol. 1, No. 1, pp. 1653-1662). Cambridge University Press.

Research Paper B:

Resilience in Product Design and Development Processes: A Risk Management Viewpoint

Shafqat, A., Welo, T., Oehmen, J., Willumsen, P. and Wied, M., 2019. Resilience in product design and development processes: a risk management viewpoint. *Procedia CIRP*, *84*, pp.412-418.

Research Paper C:

Planning Unplanned Design Iterations Using Risk Management and Learning Strategies

Shafqat, A., Oehmen, J. and Welo, T., 2021. Planning Unplanned Design Iterations Using Risk Management and Learning Strategies. *Journal of Engineering Design*, pp.1-24.

Research Paper D:

Empirical Investigation on the Role of Risk Mitigation Actions in Engineering Projects

Shafqat, A., Oehmen, J., Welo, T. and Ringen, G., (Submitted in 2021). Empirical Investigation on the Role of Risk Mitigation Actions in Engineering Projects. *Under second review in Systems Engineering Journal.*

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Part I: Introductory Overview

1. Introduction to Unplanned Design Iterations and Overview of the Thesis

This section presents the thesis' short description, describing its scope, aim, and research questions that are referred to throughout this thesis.

1.1 Background and Problem Framing: Impact of Design Iterations on New Product Development

The new product development (NPD) process is a strategic activity for businesses to create a competitive advantage (Brown & Eisenhardt, 1995; Danneels, 2002). Today's tough competition puts high pressure on companies to introduce new products to capture new markets. In the NPD process, organizations strive to optimize cost, quality and lead time (Oehmen et al., 2010; Chauhan et al., 2017). The NPD process is perceived as actions to transform different ideas into a product or a system that solves customer problems and needs (Dougherty, 1992; Woodard et al., 2013). A generic NPD process consists of six phases: planning, concept development, system-level design, detailed design, testing and refinement, and production ramp-up (Eppinger and Ulrich, 2015).

NPD projects are a vital part of their strategy for manufacturing companies to maintain a competitive advantage in a competitive environment. However, NPD projects face undesirable, unplanned design iterations due to the complexity of the product under development, unique technologies, and changing requirements due to dynamics in the market (Ballard, 2000). The literature reveals that current NPD methods cannot fully address unplanned design iterations in NPD processes (Oehmen et al., 2014, Schuh et al., 2017). Therefore, many NPD projects fail during their development processes or soon after they reach the market (Griffin and Kahn, 2009; Barczak et al., 2009).

Unplanned design iterations often occur in the way of rework when mistakes or feedback loops, unexpectedly, need a step backward in the design phase (Unger and

Eppinger 2009) (see Section 3.1 for more details). Unfortunately, proactive strategies, including risk management, often fail to manage unplanned design iterations specifically (Aven and Kristensen 2019; Thamhain, 2013). Therefore, these unplanned design iterations often cause time and cost overruns, ultimately leading to failure of the NPD projects (Mujumdar and Maheswari 2018; Eppinger et al., 1997; Krishnan et al., 1997; Smith and Eppinger, 1997; Smith and Tjandra, 1998; Sobek et al., 1999; Costa and Sobek, 2003; Jin and Chusilp, 2006).

The literature indicates that unplanned design iterations to some extent are unavoidable due to complex and uncertain product development environments (León et al., 2012). At the same time, unplanned design iterations often add value to the design process (León et al., 2012). As a result, instead of just avoiding unplanned design iterations, the focus should be on managing them to maximize the value each unplanned design iteration generates for the overall design process. In this thesis, we focus on the simultaneous use of proactive and reactive strategies for managing unplanned design iterations to maximize the value of each unplanned design iteration for the overall design phase of the NPD process.

For this thesis, we conceptualize an unplanned iteration as the occurrence of a specific category of NPD project risk. We define risk as the impact of uncertainty on the NPD project's objectives (ISO 31000, 2018), and unplanned design iterations have therefore deemed a class of uncertain events that negatively impact an NPD project's objectives, including development cost and schedule. The NPD process in engineering projects faces different risks (Kutsch et al., 2017; Zwikael and Ahn, 2011; Choi et al., 2010; Mu et al., 2009; Cooper, 2003). These risks can fall into two categories: Foreseen risks, i.e., foreseen possible, unplanned design iterations identified as a risk that occurred despite preventive mitigation actions. Unforeseen risks are unforeseen design iterations not identified during the risk management or other planning processes (Aven and Kristensen, 2019).

This thesis studies the “predict- and-plan” and the “monitor-and-react” approaches used to manage foreseen and unforeseen risk events that cause unplanned design iterations in the NPD process. The first approach under study in this thesis is the risk management-based “predict-and-plan” approach, which is named as proactive risk management (PRM) approach (see Section 3.2.1 for detailed explanation). The second approach is the “monitor-and-react” approach, which includes two fields of study: the resilience-based “monitor-and-react” approach (see Section 3.2.2 for detailed explanation); and the organizational learning based “monitor-and-react” approach (see Section 3.3 for detailed explanation).

In the PRM approach, design teams identify and assess the risks at the start of the NPD process, and afterward implement the risk mitigation actions to reduce the risk (either their likelihood of occurrence or significance of their impact) of unplanned design iterations (Unger and Eppinger 2011; Unger and Eppinger 2002). Overall, the PRM approach reduces unplanned design iterations by identifying and subsequently proactively mitigating foreseen risks. However, there remains a considerable potential to identify those risks better and develop improved mitigation actions to reduce the occurrence and impact of unplanned design iterations. This thesis studies how the PRM approach is employed in the NPD process and what type of risk mitigation actions are employed to manage the risks that cause unplanned design iterations.

The second approach under study is the resilience-based “monitor-and-react” approach (see Section 3.2.2 for explanation). This approach monitors for unplanned design iterations and, after their occurrence, enhances the NPD process’ capability to resolve the unplanned design iterations and absorb the negative impact of the unplanned design iterations on the overall progress of the NPD process. This thesis studies how the resilience-based “monitor-and-react” approach possibly complements the risk-management based “predict-and-plan” approach for managing NPD project risks that cause unplanned design iterations.

Finally, this thesis studies the learning-based “monitor-and-react”, which is named as reactive fast learning (RFL) (see Section 3.3 for more details). The RFL approach employs learning methods (inspired by organizational learning) to resolve unplanned design iterations faster and increase technical and process-related knowledge, leading to faster resolution of unplanned design iterations. This approach primarily plays a role in reducing unplanned design iterations’ adverse impact by building general organizational capabilities to efficiently deal with their occurrence. For better utilization of the RFL approach in the NPD process, this thesis investigates the practices of the RFL approach in the NPD process.

1.2 Research Questions

Against the background described in the section above, the main research question of the PhD thesis is to study the better utilization of risk management-based “predict-and-plan” and resilience-based and learning-based “monitor-and-react” approaches for managing unplanned design iterations. Therefore, the main research question of the thesis is as follows:

How can organizations better manage unplanned design iterations in NPD projects by effectively utilizing risk management, learning strategies, and resilience?

This thesis is guided by six sub-research questions to answer the main research question. Each research question connects the main areas introduced above (risk management, resilience, organizational learning, and NPD process), as shown in Figure 1 below.

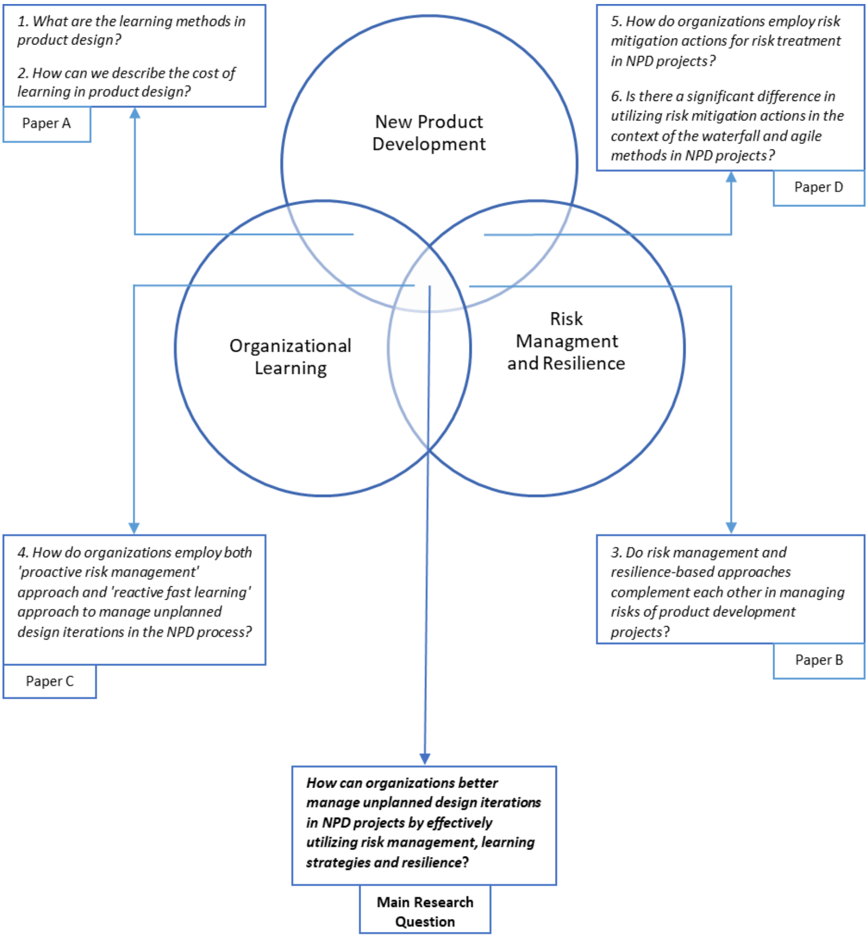

Figure 1 The scope of the thesis with research questions from appended papers (A, B, C, D).

For example, as shown in Figure 1, the first two research questions connect organizational learning with the NPD process as follows:

1. *What are learning methods in product design?* ***Paper A***
2. *How can we describe the cost of learning in product design?* ***Paper A***

The third research question combines the risk management, resilience, and NPD process as follows:

3. *Do risk management and resilience-based approaches complement each other in managing risks of product development projects?* ***Paper B***

The fourth research question incorporates risk management, organizational learning, and NPD process for managing unplanned design iterations as follows:

4. *How do organizations employ both the 'proactive risk management approach, as well as 'reactive fast learning' approach, to manage unplanned design iterations in NPD process?* ***Paper C***

For mitigating the unplanned design iteration risks, the fifth and sixth research questions again involve risk management and NPD process as follows:

5. *How do organizations employ risk mitigation actions for risk treatment in NPD projects?* ***Paper D***
6. *Is there a significant difference in utilizing risk mitigation actions in the context of the waterfall and agile methods in NPD projects?* ***Paper D***

These research questions are investigated using literature review, interview studies, and survey from Danish and US industrial perspectives. The results of these research questions are presented in four scientific articles (Papers A, B, C, and D attached in the appendix of this thesis). Each research paper contributes to the primary research question as mentioned above.

1.3 Scope of the Thesis

This thesis explores risk management, resilience, and organizational learning in the NPD process of engineering projects, as shown in Figure 1. In this study, the unit of analysis is "one project", defined as a temporary sequence of actions undertaken to accomplish and create a unique product or service (Loch et al., 2011). Within this category, the thesis focuses on the NPD process in "engineering" type projects, i.e., projects employing the creative usage of scientific principles to design or develop machines, apparatus, structures, or manufacturing processes (ECPD, 1947).

The scope of risk management is limited to project risk management. It should be noted that this thesis does not focus on safety risk management in engineering projects. However, as shown in Figure 1, project risk management overlaps with organizational learning and resilience in the NPD process.

In the resilience domain, this thesis is limited to studying “resilience properties” in the NPD process to resist and recover from unexpected design challenges (Aven, 2017; Henry et al., 2016). These properties enable the engineering projects to weaken or reverse the negative impact of unplanned design iterations on the project performance (Paper B).

Referring to organizational learning, this thesis is limited to the study of single-loop learning (Argyris and Schön, 1997) in the engineering design phase of the NPD process. More specifically, this thesis focuses on studying how learning methods are used to (quickly) resolve unexpected design challenges or unplanned design iterations in the engineering design phase of the NPD process.

Referring to the use of the two terms “new product development” (NPD) and “product development” (PD), there is a theoretical debate about the difference between “new product development” (NPD) and “product development” (PD). However, we used both terms interchangeably in the rest of the thesis.

In summary, this thesis applies risk management, resilience, and organizational learning in the NPD process of engineering projects to address and understand the academic and practitioner challenges outlined in the introduction (Sections 1.1 and 1.2).

1.4 Structure of the Thesis

This thesis consists of two parts. The first part consists of six sections, and the second part consists of four appended papers A, B, C, and D. In the first part, the first three sections present the thesis’ introduction (1. Introduction to Unplanned Design

Iterations and Overview of the Thesis), outline its approach (2. Research Methods) and review the current state of research (3. Theoretical Background).

Section 4 summarizes the results from the four research papers (Papers A, B, C, and D). Section 5 discusses the theoretical and practical implications of the results presented in the previous section. In addition, Section 5 also introduces implications for academia and practitioners, along with future work. The last section describes the concluding remarks. Finally, the second part presents the published and submitted papers to peer-reviewed international journals and conferences.

1.5 The Use of Research Papers in the Thesis

This thesis is paper based as per the PhD degree requirements of NTNU and DTU. Therefore, we have taken context from several sections of the research Papers A, B, C, and D (appended with thesis) to prepare all parts of this thesis. For example, the text from the literature review sections of the appended papers has been used in the edited form to provide the thesis's theoretical background. Similarly, the appended papers have been utilized in the preparation of the introduction section of this thesis.

2. Research Methods

2.1 Research Approach: Design Research Methodology (DRM)

This research followed the Design Research Methodology (DRM) framework as a foundation that provides a holistic framework of the engineering design research process. The DRM facilitates the employment of both problem-based and theory-based research; therefore, this method provides an opportunity to combine and address the knowledge gap between theory and practices of risk management, resilience, and organizational learning in the NPD process (Blessing and Chakrabarti, 2009). In addition, the DRM provides an adaptable way of conducting research because it does not favor any applied research methods such as case studies, surveys, or literature reviews. Instead, it promotes the use of appropriate research methods, including literature-based and empirical-based research methods. Furthermore, DRM endorses multidisciplinary research (Blessing and Chakrabarti, 2009), which is appropriate for this study.

Thus, DRM is a suitable method for supporting descriptive and prescriptive studies, which are included in this research. The descriptive study involves describing the current state. The prescriptive study involves the recommendations based on the knowledge generated during the study, including recommendations about how specific tools and frameworks should be used (Blessing and Chakrabarti, 2009). Although DRM appears to be a set of stages and supporting methods, it is not in practice. Figure 2 shows that multiple iterations within each stage and between the stages are possible in the DRM approach (Blessing and Chakrabarti, 2009). The following subsections describe each phase of the DRM research approach.

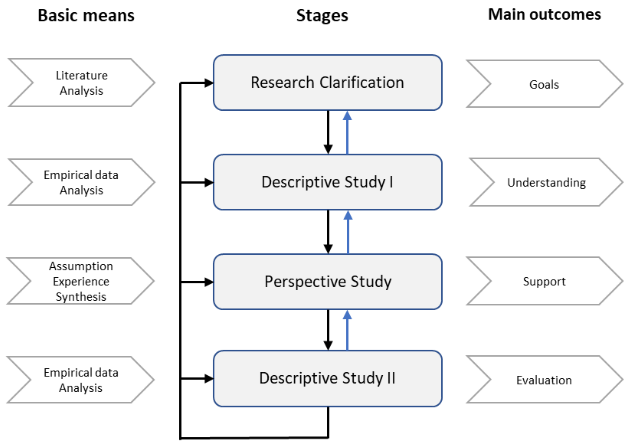

Figure 2 Design Research Methodology (DRM) framework (Redrawn based on Blessing and Chakrabarti, 2009).

2.1.1 Stage 1: Research Clarification

This stage is the starting point of the DRM research approach. It clarifies the research topic and objectives of the project by conducting an initial literature review of the research topic. The output of this stage is to provide an initial understanding of the topic and plan for the research, which is used in determining the focus of the first descriptive study (Blessing and Chakrabarti, 2009). We used this stage (in Paper A) to conceptualize the "cost of learning" from failures and mistakes and learning methods employed in the NPD process. The research clarification provided a basis for the subsequent stages of this research approach.

2.1.2 Stage 2: Descriptive Study I

This stage provides a detailed and deeper understanding of the current situation and influencing factors under investigation based on theories and models. This can be achieved from empirical studies and meta-review of the previous empirical evidence (Blessing and Chakrabarti, 2009). This stage also enables the next stage with influencing factors identified in the current stage. We used this stage (in Paper B) to understand the use of risk management and resilience in managing known and unknown NPD project risks.

2.1.3 Stage 3: Prescriptive Study I

Stage 3 of the DRM research approach conceptualizes the supportive prescriptions by engaging the factors identified in the descriptive study I. A supportive prescription may include such as, but not limited to, tools, methods, checklist, guidelines, knowledge, etc. The goal of the prescriptive study is to enhance, reduce or eliminate the influence of the critical factors found in the descriptive study I. This stage will test the prototypical implementation of the framework developed in stage 2 by using case studies. Interviews and surveys in case companies will assess the performance of the proposed framework. We used this research stage (in Papers C and D) to explore the risk management-based "predict-and-plan" approach and learning-based "monitor-and-react" approach. This stage also provides recommendations for how to employ both approaches in managing unplanned design iterations. We used a cross-sectional interview study (Bell et al., 2018) to conduct this research.

2.1.4 Stage 4: Descriptive Study II

The goal of descriptive study II is to evaluate the performance of the developed supportive prescription or framework. The performance is typically evaluated through empirical studies, which can be of different types. This stage documents the developed supportive framework's performance and prepares a practitioner handbook for industrial practitioners (Blessing and Chakrabarti, 2009). In this research work, we did not employ this research stage due to the time limitation of the PhD project. This stage can be employed in future work to explore the current research topic further.

2.2 Applied Research Methods

Table 1 Applied research methods used in research papers

Papers	Research Question	Methods	Contributions
Paper A, *"The cost of learning from failures and mistakes in product design: Reviewing the literature."*	(1) What are learning methods in product design? (2) How can we describe the cost of learning in product design?	A review of the product development literature. **(DRM Phase: research clarification)**	C1: Paper A conceptualizes the cost of learning from failures and mistakes in the design phase of the PD process. C2: Paper A identifies and categorizes the learning methods in the design phase of the PD process.
Paper B, *"Resilience in Product Design and Development Processes: A Risk Management Viewpoint"*	(3) Do risk management and resilience-based approaches complement each other in managing risks of product development projects?	A semi-structured interview study involving seven project managers and engineers across three firms in Denmark. **(DRM Phase: descriptive study I)**	C3: Paper B finds that all three organizations predominantly implemented either a "predict-and-plan" approach or a "monitor-and-react" approach to mitigate the impact of unknown risks and surprises in their PD projects. C4: Paper B reveals that resilience and risk management approaches complement each other as a strategy to address both known and unknown risks. C5: Paper B also reveals that the "predict-and-plan" approach is well established in the three companies we studied. In contrast, the resilience-based "monitor-and-react" approach is less established as a strategy for handling surprises in the design process.
Paper C, *"Planning Unplanned Design Iterations Using Risk Management and Learning Strategies"*	(4) How do organizations employ both 'proactive risk management' approach and 'reactive fast learning' approach to manage unplanned design iterations in the NPD process?	A semi-structured interview study involving 14 interviewees including CEO, director R&D, project managers, risk managers and design engineers across eight firms in Denmark. **(DRM Phase: Prescriptive Study I)**	C6: Paper C finds that the PRM approach is better established than the RFL approach for managing unplanned design iterations. C7: Paper C reveals that the engineering design teams lacked a structured approach to select the most suitable learning methods for resolving the unplanned design iterations after their occurrence. C8: Paper C observes that organizations failed to convert the new technical and process knowledge (gained during resolution of unplanned design iterations) into organizational learning.
Paper D, *"Empirical Investigation on the Role of Risk Mitigation Actions in Engineering Projects"*	(5) How do organizations employ risk mitigation actions for risk treatment in NPD projects? (6) Is there a significant difference in utilizing risk mitigation actions in the context of the waterfall and agile methods in NPD projects?	A statistical analysis of the survey study that was conducted in six large-scale aerospace and defense firms in the USA. **(DRM Phase: Prescriptive Study I)**	C9: Paper D indicates that the classification of risk mitigation actions in the statistical analysis was found in line with the literature-based questionnaire. C10: Paper D reveals a surprising finding indicating that the individual risk mitigation actions showed significance with the impact of various types of NPD project risks. C11: Paper D shows that all the selected risk mitigation actions from survey data collectively showed explanation power for treatment, in some way, to the NPD project risks. C12: Paper D did not find a significant difference for utilizing risk mitigation actions in NPD projects employing waterfall, agile or both methods.

2.2.1 Literature Review

This research employed a critical literature review to identify knowledge gaps and contradictions in previous studies (Bell et al., 2018). This method is also used for a deeper and more structured analysis of the literature sources.

As shown in Table 1, Paper A presents the structured and critical literature review to address the literature gap regarding the “cost of learning” and “learning methods” in the engineering design phase of the product development (PD) process. In this literature review, we used Boolean operators (OR and AND) and search strings. The search strings include (“product development process” AND learning), (“product development process” AND learning AND cost), (innovation AND “learning cost”), and (“product design” AND “learning cost”). This literature review focused on peer-reviewed papers' titles, keywords, and abstracts without limiting the search to specific publication dates. In the initial screening, we read the titles of the papers. In the final screening of the papers, we read the papers’ abstracts, introduction, and conclusion. Further, we identified additional relevant literature after backward referencing from the selected articles. Using literature review, paper A conceptualized the cost of learning and identified the learning methods in the engineering design phase of the PD process.

In addition to Paper A, we conducted a critical literature review in Paper C and Paper D. In paper D, we conducted critical literature reviews on the topics, including planned and unplanned design iterations in the engineering design phase of the NPD process. In paper D, we conducted empirical reviews on utilizing risk mitigation actions in NPD projects for risk treatment. In paper D, we also conducted a literature review of the empirical studies on the risk mitigation in engineering projects utilizing waterfall or agile NPD methods.

2.2.2 Case Study

Paper B includes a case study conducted in large international companies in the medical industry with their headquarters in Denmark. We selected the case study as a research method to examine how and why questions and generate rich empirical data (Yin, 2017). It is noteworthy that case studies are well-suited in the critical early phases of the new management theory when key variables and their relationship need to be explored (Gibber et al., 2008; Eisenhardt, 1986).

Therefore, the case study was well suited for an in-depth study of risk management and resilience practices in a real-world scenario. In the case study conducted for this research work, we investigated an ongoing PD project where the authors had no control over the environment. The further details of the method can be seen in appended Paper B.

2.2.3 Interview Studies

In Paper B and Paper C, we selected semi-structured interviews as a primary data source to gain a detailed understanding of risk management and learning practices in the NPD process. The semi-structured interviews were chosen as the empirical elements of Paper B and Paper C, following a deductive research approach (Bell et al., 2018). In this research, the semi-structured interviews allowed us to collect rich data quickly from multiple sources (Eisenhardt and Graebner, 2007). In addition, in semi-structured interviews, we endeavored to achieve reliability and consistency by using an interview script that established the topics to be addressed during the interviews (Paper B and Paper C).

In Paper B, we conducted seven semi-structured interviews in three companies with project managers and design engineers. In Paper C, we conducted fourteen interviews with the CEO, R&D director, project managers, and design engineers in eight selected companies that were all deeply involved in NPD projects. We conducted face-to-face interviews with eleven participants and held three remaining interviews over the phone with participants.

Overall, in Paper B and Paper C, twenty-one interviews were conducted in eleven Danish companies. The case companies were selected based on a set of criteria: (1) companies with ongoing NPD projects, (2) physical products, (3) companies with in-house product development, and (4) headquartered in Denmark. To ask for participation in the study, we contacted the interviewees via email, clearly explaining the purpose of the research.

In Paper B, during the interviews, the interview script included a combination of open and closed questions focusing on three topics: 1) how risk management was performed in the PD process; 2) why risk management failed to treat PD process risks; 3) and how resilience-based practices enhanced the organization's ability to address unknown risks in the PD process. In Paper C, the interview script combined open and closed questions, aiming to explore three topics 1) how PRM was performed in the NPD process, 2) when and how PRM failed to mitigate (foreseen and unforeseen) risks of unplanned design iterations, and 3) how RFL approach helped or failed to reduce the impact of unplanned design iterations due to foreseen and unforeseen risks in NPD process.

During the interviews, the 'snowballing' (Bell et al., 2018) technique was employed as the sampling strategy due to the study's exploratory nature. The participants were asked to provide as much detail as possible regarding their experiences. "What if" questions were asked to determine the participant's perceptions about matters asked during the interviews. The interviews were recorded in Paper B and Paper C, which lasted for 45 to 60 minutes, on a digital audio recorder and transcribed using a professional transcription service.

2.2.4 Analysis of the Survey Data

In Paper D, we used the survey research method to investigate the role of risk mitigation actions in treating NPD project risks, based on existing survey data (Oehmen et al., 2014). We selected survey as a research method because it enables investigating the "who", "what", "where", and "how many" questions (Yin, 2017). The survey also enables gathering large random samples of the population under investigation. The large random samples provide the most accurate estimates of what is true in the population, which provide data samples.

We analyzed the survey response conducted by one co-author in Paper D (Oehmen et al., 2014). Other authors were not involved in the survey development and distribution process. The survey questionnaire addressed 1) characteristics of organizations; 2) characteristics of development programs; and 3) risk management practices such as risks and their impact and risk mitigation. The survey questionnaire was developed with the consensus of twelve individuals, representing one risk management consultancy, three academics institutions, and six companies from the aerospace and defense industry.

In Paper D, we analyzed the survey response using four statistical methods. First, the Effect Likelihood Ratio Test (Sheskin, 2020) was used for the initial screening of risk mitigation actions. This method was again used for investigating the effect of each selected risk mitigation action on the individual risk impact. Second, Goodman Kruskal's Gamma method (Sheskin, 2020) measured the strength of association between risk mitigation actions. Third, Ordinal Logistic Regression (Sheskin, 2020) was used to explore the explanation power of all the mitigation actions for individual risk. Finally, Kruskal-Wallis H test (Meyer and Seaman, 2006) was used to analyze the practices of risk mitigation actions in NPD projects using waterfall, agile, or both NPD methods. The appended Paper D provides a detailed explanation of the aforementioned statistical methods (see Section 3.3 Statistical data analysis of appended Paper D).

The appended papers (A, B, C, and D) will include the state-of-the-art relevant to the specific contribution each one of them represents. The following section will elaborate on the theoretical basis behind the research presented in this thesis.

3. Theoretical Background

This section aims to provide a broad background of the theory, which will lead up to the study's research questions. Borrowing from and building on the literature sections of the appended papers (A, B, C, and D), this section summarizes the most important findings from the relevant literature. The following subsections present the theoretical background corresponding to the thesis scope outlined in Section 1, including NPD process, risk management, resilience, and organizational learning in the NPD process.

3.1 New Product Development Process and Design Iterations

This subsection presents an overview of the NPD process concerning the scope of this thesis and the research questions investigated in research papers.

Today companies operate in a competitive environment and consider product innovation a significant success factor (McDermottand, 2002). In addition, a competitive environment puts high pressure on companies to introduce new products to capture new markets. Therefore, organizations that develop new products use various procedures and methods to design, develop, and launch new products in the market, categorized under new product development (NPD) (Ulrich and Eppinger 2016).

Figure 3 Generic product development process from Eppinger (Eppinger and Ulrich, 2015)

A generic product development process is shown in Figure 3. The range of NPD processes varies from a highly rigid and plan-driven approach (stage-gate and waterfall) to very flexible approaches (spiral and agile) that are used to meet increasingly fast-changing requirements (Eppinger and Ulrich, 2015; Cooper, 1990; Wu and Wu, 2014).

The application scope of the NPD process for this thesis is limited to the design phase of the NPD process. The product design phase plays the primary role in defining the physical form and function of the product. The design phase involves various activities from, for example, the areas of engineering design (mechanical, electrical, software, etc.) and industrial design (user interface, aesthetics, and ergonomics) (Eppinger and Ulrich, 2015). However, this thesis focuses on the engineering aspect of design phase only.

In the engineering design phase, NPD projects are becoming more complex as they become more unique and requirements change due to dynamics in the market. Therefore, NPD processes face significant risks and surprising challenges, which cause failures to achieve targets of development cost, time-to-market, and quality of the products (Francis et al., 2010; Oehmen et al. 2010; Chauhan et al. 2017; Awny, 2006; Unger and Eppinger, 2009; Wu and Wu, 2014). A study revealed that only 15% of new product ideas and around 60% of NPD projects achieve commercial success in the market (Griffin and Kahn, 2009). NPD projects fail due to the undesirable design iterations in the NPD process (Ballard, 2000). A survey-based empirical study of design teams has revealed that design teams spent up to 50% of design time on unnecessary or unwanted design iterations (Ballard, 2000).

Design iterations comprise work containing correction, interdependency, or feedback (Unger and Eppinger, 2002). The existing body of research on 'design iterations' in the NPD process has been restricted to the early detection of potential design iterations to avoid or plan the design iterations (Mobin and Hijawi, 2020; Shajahan et al., 2019; Wynn and Eckert, 2017; Unger Eppinger, 2011; Wynn et al., 2007; Meier et al., 2007). For example, to plan or avoid design iterations, some studies suggest predictions of design iterations using design structure matrices, buffering the design phase, modeling of the design process (Wynn et al., 2007), using genetic algorithms, and selecting suitable product development methods (Meier et al., 2007). These methods address identification and sequencing 'planned design iterations' to enhance planning in the

NPD process. However, we argue that these techniques are poorly suited to managing unplanned design iterations because of their focus on predictability—and thus ‘plannable’ design iterations.

As mentioned above, design iterations involve work containing correction, interdependency, or feedback (Unger and Eppinger, 2002). However, explicitly, unplanned design iterations often appear in the form of rework when mistakes or feedback loops unexpectedly require a step backward in the design phase (Unger and Eppinger, 2009). Therefore, unplanned design iterations often cause delays and cost overrun in NPD processes, as documented in the literature (Mujumdar and Maheswari, 2018; Eppinger et al., 1997; Krishnan et al., 1997; Smith and Eppinger, 1997; Smith and Tjandra, 1998; Sobek et al., 1999; Costa and Sobek, 2003; Jin and Chusilp, 2006). However, by the very nature of the NPD process, design iterations are unavoidable and are, in many cases, essential to create value in the design phase of the NPD process (Krehmer et al., 2009).

Although unplanned design iterations are generally unavoidable to create value in the design process (León et al., 2012), they are often a significant source of change risk propagation in the NPD process (Li et al., 2020). Therefore, instead of solely aiming to avoid unplanned design iterations, the aim should also be to manage unplanned design iterations and maximize the value each iteration generates for the overall design process (León et al., 2012). Hence, this thesis aims to understand the management of unplanned design iterations in the NPD process. Research question number 4 in Figure 1 addresses the knowledge gap identified in this section.

The NPD projects investigated include highly complex physical engineering products and involve different NPD project risks and unplanned design iterations.

3.2 Risk Management in New Product Development Process

Fundamentals of Risk Management

It is imperative to discuss the concept of risk before discussing risk management in the NPD process. The definition of risk and risk management has been evolving throughout history (Bernstein, 1998), and still, there is no agreement on the definition in the risk sciences (Aven, 2012). However, the well-accepted definition of risk encompasses positive (opportunity) and negative (threat) aspects. The project management body of knowledge (PMI) describes risk as *"an uncertain event or condition that, if it occurs, has a positive or negative impact on project objectives"* (PMI, 2021).

However, the papers in this thesis only focus on identifying and managing negative aspects of the uncertain event that can impact the NPD project's objectives. In the empirical studies of this thesis, we analyzed the risks that can cause undesirable, unplanned design iterations in the NPD process. Therefore, we adopt the definition of risk from the ISO 31000 (2018) standard as "risk being the effect of uncertainty on the NPD process's ability to meet its objectives". Uncertainties about critical events that may affect the performance of NPD projects are the causes of risks (Bassler et al., 2011). In a literature review, Oehmen et al. (2020) presented three fundamental sources of uncertainties that cause risks in NPD projects such as management (e.g., risks arise from organization and processes), technology (e.g., risks arise from technology maturity), and market (e.g., risks arise from changing customer expectations).

Risk management is an essential part of NPD projects (Oehmen et al., 2010). In the design phase of the NPD process, design teams generally employ a risk management strategy to identify and manage risks in the NPD process. The ISO risk management standard defines risk management as a set of coordinated activities to direct and control an organization with regard to risk (ISO, 2018). According to the ISO 31000 (2018) standard, as shown in Figure 4, the core elements of the risk management process are as follows: establishing the context, risk assessment (including risk identification, risk analysis, and risk evaluation), risk treatment, monitoring and review, and communication and consultation. The papers in this thesis use the definition of risk management in the NPD context as "the process to uncover and manage risks in the NPD process, following a structured approach by initiating timely mitigation actions to avoid, transfer or reduce risk likelihood or impact". This definition is based on the Australian risk management standard (AS/NZS, 1999) and ISO risk management standard (ISO, 2018).

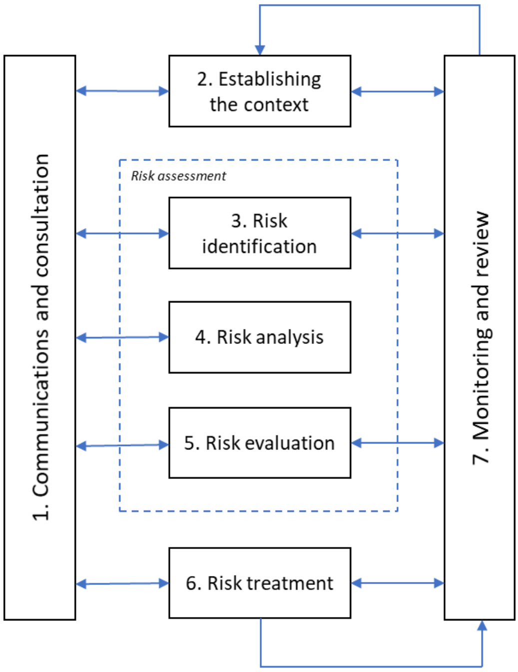

Figure 4 The ISO standard's explanation of the risk management process (Source, (ISO, 2018)).

Proactive Risk Management (PRM) in New Product Development

This subsection will discuss the risk management-based predict-and-plan approach (adopted by product management) for managing risks in the NPD process. In the initial phase of the NPD process, design teams generally try to assess the potential risks in the risk assessment phase (Oehmen et al., 2020). As shown in Figure 4, risk assessment, an integral part of the risk management process, performs a proactive role in identifying, analyzing, and evaluating potential risks in the NPD process. Subsequently, risk assessment in the NPD process facilitates organizations to plan suitable mitigation actions for treating identified risks (Oehmen et al., 2020; ISO 31000, 2018)

Therefore, considering risk management's proactive approach to identifying and mitigating risks, traditional risk management can be deemed as proactive risk management (PRM) approach in the NPD process. Design teams use different tools and techniques to employ a PRM approach to predict and evaluate the risks in the NPD process. The tools and techniques typically used in risk assessment, according to ISO/IEC standard (IEC 31010, 2019), are shown in Table 2, which summarize suitable tools and techniques used in the risk assessment (including risk deification, analysis, and evaluation) phase of the risk management process.

Literature shows that PRM usually fails to identify all the risks in the initial phase of the NPD process (Aven and Kristensen, 2019; Thamhain, 2013). PRM fails to identify all risks due to the high uncertainty and complexity associated with NPD, accompanied by a lack of (structured) process and technical knowledge necessary to successfully employ PRM methods (Aven and Kristensen, 2019). Therefore, it is likely that design teams overlook risks using PRM in the initial phase of the NPD process.

Table 2 Tools and techniques employed in risk assessment phase adopted from Paper B (IEC 31010, 2019)

Tools and techniques	Risk assessment		
	Risk identification	Risk analysis	Risk evaluation
Delphi	SA[1)]	NA[2)]	NA
Brainstorming	SA	NA	NA
Checklists	SA	NA	NA
Primary hazard analysis	SA.	NA	NA
Hazard and operability studies (HAZOP)	SA.	A[3)]	A
Root cause analysis	NA.	SA.	SA.
Failure mode effect analysis	SA.	SA.	SA.
Fault tree analysis	A	A	A
Event tree analysis	A	A	NA
Cause and consequence analysis	A	A	A
Cause-and-effect analysis	SA	A	NA
Decision tree	NA.	SA	A
Bow tie analysis	NA	SA	A
Monte Carlo simulation	NA	NA	SA
FN curve	A	SA	SA
Risk indices	A	SA	SA
Consequence/probability analysis	SA.	SA	A

1) Strongly applicable
2) Not applicable
3) Applicable

Previous studies indicate that unidentified risks affect the performance of the NPD process (Thamhain, 2013; Oehmen and Rebentisch, 2010; Kiezer et al., 2005). For example, Thamhain (2013) argues that the risk assessment phase generally fails to predict most of the risks in the NPD process, and the unidentified risks affect the performance of the NPD process in later stages. However, far too little attention has been paid to studying the better utilization of PRM approach in combination with other risk treatment approaches in the NPD process (Paper B; Paper C). Therefore, Papers B and C study the “predict-and-plan” based PRM approach along with resilience and learning-based "monitor-and-react" approaches. As shown in Figure 1, research questions 3 and 4 address the PRM approach in the NPD process.

In the PRM approach, after assessing the potential risks in the NPD process, risk treatment phase or risk mitigation phase plans risk mitigation actions (Herrmann, 2015). These are practical actions intended for reducing threats to the NPD project's success by reducing their likelihood of occurrence and impact (Bannerman, 2007). The general risk mitigation actions or strategies are classified as 'reduce', 'transfer', and 'avoid' (zur Muehlen and Ho, 2005).

However, sometimes the risk mitigation phase shows poor performance (Kiezer et al., 2005) even after employing risk mitigation actions. Previous studies on risk management emphasized the identification and classification of different risks (Schulte and Hallstedt, 2018; Willumsen et al., 2017; Stosic et al., 2017; Hall and Wiggins, 2016; Mansor et al., 2016; Akram and Pilbeam, 2015; Oehmen et al., 2014; NASA, 2011). So far, however, there has been little discussion about the employment of suitable risk mitigation actions in the context of NPD projects. Therefore, in this thesis, Paper D studies NPD risk mitigation actions employed by design teams. As shown in Figure 1, research questions 5 and 6 address the risk mitigation actions.

3.3 Resilience in New Product Development Process

Since its inception, resilience thinking has been utilized in a wide range of business-related situations, including organizations (Burnard, 2018), supply chains (Sheffi and Rice, 2005), and business models (Hamel and Valikangas, 2004). The current concept of resilience was proposed by Holling (1973) to describe ecological systems that persist in unpredictable conditions. Here, Holling (1973) made an important distinction between systems designed for resilience and systems designed for stability. Holling (1973) developed two ideas from the study of natural systems to the management of man-made systems: First, regardless of the sophistication of up-front planning, unavoidably, important future events will be unexpected. Secondly, Holling (1973) advocated substituting the prediction of unforeseen events with the capacity to absorb and accommodate unanticipated events in whatever form they may arise.

The field of resilience is growing rapidly and expanding its application area, particularly in the contexts of safety and infrastructure (Aven, 2019). In the engineering discipline, the safety engineering community (Aven, 2017) introduced the concept of resilience, which is relatively new compared to other disciplines (Bhamra et al., 2011; Sheffi and Rice, 2005; Hamel and Valikangas, 2004; Burnard, 2018). By enhancing the system's resilience, the system's safety can be improved without performing risk calculations (Aven, 2019). While in traditional risk management, it is required to perform calculations, for example, by modeling impact-probability distributions. For a resilience approach, that is not strictly necessary (Aven, 2019).

Closer to the field of NPD, project resilience was defined by Crosby (2012) as *"the ability to recover from, or adjust easily to, misfortune or change".* In this way, Kutsch and Hall (2016) differentiated resilient project management from what he called 'rule-based' project management, a stability-focused approach, as illustrated in Figure 5. In the NPD perspective, we define resilience as the capability of a system to sense, recognize, absorb and adapt to the changes, disturbances, variations, surprises, and disruptions (Aven, 2017; Bhamra et al., 2011; Oehmen and Seering, 2011). As an approach of the NPD process, resilience focuses on retaining 'post-surprise' options under the assumption that surprise is inevitable. Figure 5 shows two managerial practices, including a) stability-focused and b) resilience-focused, practiced in NPD projects.

In operationalizing the resilience concept, Carpenter et al. (2013) asked: "resilience of what to what?", separating system performance "of what" from system uncertainties "to what?". Applying Carpenter's question to the NPD process, system performance involves development time, cost, and product quality. At the same time, uncertainties consist of significant risks influencing the product's cost, development time, and quality.

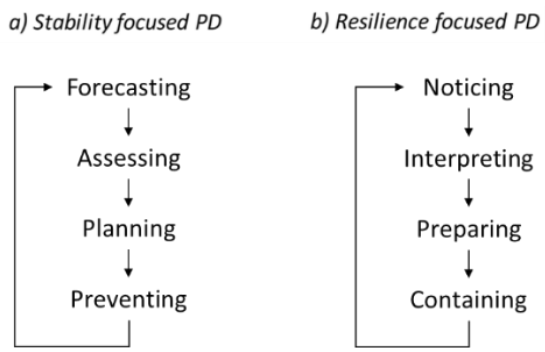

Figure 5 Two contrasting managerial practices adopted from (Kutsch and Hall, 2016).

Oehmen et al. (2014) and Schuh et al. (2017) argue that current NPD approaches are not fully capable of addressing changes in the NDP process (Barczak et al., 2009; Oehmen et al., 2014). Risks in the PDP process are often addressed reactively instead of using the PRM approach (Oehmen et al., 2012). This approach can be named a resilience-inspired “monitor-and-react” approach. In this resilience-based approach, the design engineers monitor the situation in the NPD process and prepare to react according to the situation. For example, the design engineers face unexpected design challenges and strive to engage the viable solutions in a short duration. Aven (2019) argues that, in general, proactive risk management and resilience management complement each other. He emphasizes that resilience analysis and management today is an integrated part of the risk field and science. Therefore, we hypothesize that, in most cases, introducing a resilience-inspired “monitor-and-react” approach to NPD risk management may enhance the capability of the NPD process to identify, analyze and mitigate the technology, requirement, and organizational risks.

In this thesis, we follow the argument of Aven (2019) to adopt a holistic approach integrating risk management and resilience-based thinking. This approach promotes considering both resilience and risk management perspectives as complementary to each other. Following this argument, a risk analysis framework is required to give proper direction to a resilience approach. Moreover, resilience approaches add reactive and adaptive capabilities that are not covered by risk management. This thesis transfers this argument to the NPD process and investigates the potential of integrated risk management and resilience approaches to improve the NPD process. Therefore, Paper B investigates research question number 3, as shown in Figure 1.

3.4 Organizational Learning in New Product Development Process

The corporate world mainly utilizes the term "learning" from an organizational perspective (Senge 1991). However, there is also a tendency in the academic community to study learning in the context of NPD (Un and Rodríguez 2018; Cui et al., 2014; Akgün et al., 2006; Lynn et al., 2003; Lynn et al., 1996). In the NPD process, learning activities enhance the ability of the design teams to address design challenges arising in the design phase of the NPD process (Paper A). Schulze et al. (2013) define learning as *"processes of information or knowledge acquisition, distribution, interpretation, and storage".*

Likewise, Persidis and Duffy (1991) state that *"designers learn when they encounter knowledge which is sufficiently different from their present state of knowledge".* Persidis and Duffy (1991) explain that learning consists of three sub-processes, including (1) acquisition, (2) generation, and (3) modification. They further clarify that the (1) acquisition represents the process to receive new knowledge or information; (2) the generation presents creating new from the general knowledge; and (3) the modification describes the process of altering the general knowledge.

In the context described by Persidis and Duffy (1991), the papers in this thesis consider that learning happens when the design teams encounter design challenges and obtain new knowledge besides with the technical knowledge and process-related knowledge; generate solutions to manage design iterations by tailoring the existing knowledge; and increase the technical knowledge and process-related knowledge at the individual, team and organizational levels.

To further understand learning in the NPD process, we consider single-loop and double-loop learning theories Argyris and Schön (1997) proposed at the organizational level. Argyris and Schön (1997) describe single-loop learning as a process of error detection and correction, which permits the organization to follow its current policies. To describe learning associated with the NPD process in the context of single-loop learning, we take the example of managing unplanned design iterations in the engineering design phase of the NPD process. Engineering design teams obtain new knowledge and develop new (technical) solutions on the product level to resolve unplanned design iterations. During this process, the requirements of the NPD project remain the same, and the NPD project execution processes also remain unaffected. Moreover, the engineering design teams successfully manage the unplanned design iterations, which can be associated with single-loop learning.

Argyris and Schön (1997) refer to double-loop learning as a process that modifies the organization’s fundamental policies and objectives in error detection and correction. To explain double-loop learning in the context of the NPD process, we take the example of the improvements in the organization’s standard operating procedures related to problem-solving process or NPD project management as a result of new knowledge gained in managing unplanned design iterations (including improvements to the risk management process).

Therefore, the new solutions to the problems improve the product itself and enhance the organization's entire knowledge, which can improve ongoing and future projects. For example, Technical Review Boards, such as those used after the explosion of a Concorde jet in 2000, exemplify double-loop learning at the level of an entire industry (Cusick et al., 2017).

As mentioned above, in learning loops, design teams enhance technical knowledge and process-related knowledge by using different methods for knowledge acquisition, generation, and modification collectively labeled as ‘learning methods’ (Schulze et al., 2013; Dalmaz et al., 2015). In the NPD process, learning methods (Paper A) are often utilized to manage unplanned design iterations quickly. The approach which utilizes learning methods to primarily reduce the adverse impact of unplanned design iterations by building general organizational capabilities (to deal with their occurrence more effectively) can be labeled as "reactive fast learning" (RFL).

The RFL approach utilizes learning methods to enhance technical and process-related knowledge (Argyris and Schön, 1997). For example, an unforeseen introduction of new technology in a sub-system can cause an unplanned design iteration. It can be managed, as it emerges, by accelerated learning through fast testing of the technology and tools. In conclusion, the RFL approach reduces the adverse impact of unplanned design iterations by faster resolution using learning strategies.

For managing unplanned design iterations, the effective employment of the RFL approach in the NPD process can only be possible if engineering design teams understand how and when the RFL approach is suitable to be employed in its specific real-world scenarios (Henshall et al., 2017). However, to our knowledge, there have been no empirical studies investigating when or how organizations use the RFL approach, what kind of learning methods are used and how the RFL approach performs in managing undesirable unplanned design iterations in the NPD process. Therefore, in a real-world scenario, this thesis explores utilizing the RFL approach by product development organizations in managing unplanned design iterations. For this, in Papers A and C, we investigate the research question numbers 1, 2, and 4, as shown in Figure 1.

4. Main Results from Literature Review, Interview Studies and Survey Data Analysis

4.1 Paper A: The Cost of Learning from Failures and Mistakes in Product Design: Reviewing the Literature

Table 3 Overview of Paper A

Title	The cost of learning from failures and mistakes in product design: Reviewing the literature
Authors	Ali Shafqat (main author), Josef Oehmen, Torgeir Welo and Pelle Willumsen
Aim	Paper A aims to investigate (a) the concepts of cost of learning and (b) learning methods in the product development (PD) process's design phase.
Research Question	(1) What are the learning methods in product design? (2) How can we describe the cost of learning in product design? (RQs 1 & 2 as shown in Figure 1)
Method	A review of the product development literature.
Contribution of the Paper	• Paper A conceptualizes the cost of learning from failures and mistakes in the design phase of the PD process. • Paper A identifies and categorizes the learning methods in the design phase of the PD process.
Main Author's Contribution	The main author conducted the literature review and led the writing of the article with inputs from co-authors. In addition, co-authors also guided the main author in finalizing the scope of the study and research questions.
Publication Status	Published in *Proceedings of the 22nd International Conference on Engineering Design (ICED19),* Delft, The Netherlands, 5-8 August 2019. DOI:10.1017/dsi.2019.171

4.1.1 Brief Description about Conceptualizing the Cost of Learning

Most new products encounter significant uncertainties and risks in the engineering design phase. Uncertainty is usually associated with a lack of information, while learning is a process that acquires information. Therefore, learning fast and at a low cost decreases the uncertainty and increases the efficiency of the product design phase. There is a significant body of studies on individual, team, and organizational learning. However, there is a gap in the literature review on the cost of learning in the design phase of the engineering product development process. Therefore, this paper investigates the concept of cost of learning in the engineering design phase. Reviewing the literature, this paper conceptualized the cost of learning and identified the learning methods while studying three aspects in the design phase of the PD process including: (1) costs connected with learning from mistakes and failures, (2) categories of learners, and (3) learning methods. This paper used the literature review method, as shown in Table 3. Paper A contributes to answering research questions 1 and 2, as given in Figure 1.

4.1.2 Main Results from Literature Review

This subsection presents the literature review's key findings related to conceptualizing the cost of learning and identifying the learning methods. The key findings are as follows:

- This paper has defined the cost of learning in the design phase as time and money, as shown in Table 5. Time as the cost of learning is further categorized as time overrun due to outsourcing learning. Finally, money as the cost of learning is subcategorized into design failure and design rework. Table 4 shows the categories of the cost of learning in the engineering design phase of the product development process.
- The paper has also identified that the general categories of learners in the product design phase are individual product designers and design teams.
- Reviewing the literature, we categorized the learning methods in the design phase into formal and informal learning methods. Learning methods such as learning by doing, prototyping, outsourcing, consulting past product reviews, and learning through training and lectures are included in the formal learning methods category. Learning from incidents is included in the informal learning methods category.

- In the literature, we find that the selection of learning methods is claimed to affect the cost of learning. However, one of the more significant findings emerging from this paper is that risk analysis can reduce learning costs in the product design phase.

4.1.3 Contributions to Answering Research Questions 1 and 2

In the current paper, the first research question is *"What are the learning methods in product design?"* Table 4 addresses the first research question and illustrates that different learning methods exist in product design.

Table 4 Learning methods in the engineering design phase

Learning Method	**Categories of learning methods**	**Reference**
Learning through knowledge acquisition, training, and lectures	Formal	(Yuan Fu, Ping Chui, & Helander, 2006), (Henshall et al., 2017)
Learn by doing	Formal	(Cui et al., 2014), (Henshall et al., 2017)
Learning from incidents and failures	Formal/Informal	(Drupsteen & Guldenmund, 2014), (Henshall et al., 2017)
Prototyping and experiments	Formal	(Erichsen et al. 2016)
Learning from teammates and coaches	Informal	(Leifer & Steinert, 2011)
Outsourcing	Formal	(Un & Rodríguez, 2018)
Past product reviews, customers	Formal	(Lynn et al., 2003)

Table 5, which relates to the second research question, illustrates that the cost of learning can be divided into two categories: time and money.

Table 5 Categories of the cost of learning in the engineering design phase

Cost of learning	Category	Reference
Time overrun due to outsourcing learning	Time	(Kessler et al., 2000), (Postrel, 2002)
Design failure, Design rework	Money	(Del Río et al., 2014), (Lilly & Porter, 2003), (Smite & van Solingen, 2016), (Henshall et al., 2017), (Drupsteen & Guldenmund, 2014)

4.1.4 Brief Reflection on Contributions

The paper's findings contribute in several ways to our understanding of the cost of learning in the engineering design phase of the PD process. This paper thus gives the conceptual foundations for Paper C to improve the efficiency of the PD process by reducing the cost of learning from failures and mistakes.

4.2 Paper B: Resilience in Product Design and Development Processes: A Risk Management Viewpoint

Table 6 Overview of Paper B

Title	Resilience in Product Design and Development Processes: A Risk Management Viewpoint
Authors	Ali Shafqat (main author), Torgeir Welo, Josef Oehmen, Pelle Willumsen and Morten Wied
Aim	This paper aims to explore a resilience-inspired "monitor-and-react" approach and risk management-based "predict-and-plan" approach for managing product development (PD) project risks.
Research Question	Do risk management-based "predict-and-plan" approaches complement the resilience-based "monitor-and-react" approach for managing risks in the product development process? (RQ 3 as shown in Figure 1)
Method	A semi-structured interview study involved seven project managers and engineers in Denmark across three firms (P1, P2, and P3).
Contribution of the Paper	• Paper B shows that all three organizations predominantly implemented either a "predict-and-plan" approach or a "monitor-and-react" approach to mitigate the impact of unknown risks and surprises in their PD projects. • Paper B reveals that resilience and risk management approaches complement each other as a strategy to address both known and unknown risks. • Paper B also reveals that the "predict-and-plan" approach is well established in the three companies we studied. In contrast, the resilience-based "monitor-and-react" approach is less established as a strategy for handling surprises in the design process.
Main Author's Contribution	The main author conducted the case study interviews, while another co-author conducted additional interviews. In addition, co-authors provided input in the data analysis and writing process.
Publication Status	Published in *Procedia CIRP*, 84, pp.412-418. https://doi.org/10.1016/j.procir.2019.04.248

4.2.1 Brief Description about Risk Management and Resilience in Product Development

This paper argues that traditional product development (PD) risk management tools and methods are based on the "predict-and-plan" paradigm, assuming that we have enough time and resources to identify, analyze, and mitigate the product development project risks and organizational risks. However, the "reality of the product development process" is that we usually have neither. At the same time, we are confronted with an accelerated introduction of uncertainty, for example, by pervasive digitalization. This paper, therefore, explores the resilience-inspired "monitor-and-react" approach and risk management-based "predict-and-plan" approach, which complements each other in managing PD project risks. This paper used a semi-structured interview study to investigate the research question, as shown in Table 6.

4.2.2 Main Results from the Interview Study

- To identify and mitigate the risks in the design phase of the PD process, interviewees from all three companies shared the same opinion on using the risk management-based "predict-and-plan" approach.
- To identify risks, all project managers and design engineers used the brainstorming technique in the early phase of the PD project.
- The project managers and design engineers in all three companies categorized significant risks as delay in time to market, development cost of the PD project, and product manufacturing cost.
- All three companies encountered unexpected "surprises" which were not identified during risk assessment in the early phase of PD projects.
- The analysis of the interview study indicated that design engineers and project managers employed resilience-focused actions in response to unknown risks and surprises. However, most of the companies did not focus on enhancing their resilience capabilities.
- Overall, these results suggest that the risk management part was better formalized than the resilience part.

4.2.3 Contributions to Answering Research Question 3

This paper investigates the following research question: *Do risk management based "predict and plan" approach complement the resilience-based "monitor and react" approach for managing risks in the product development process?*

In answer to the research question, the analysis of the empirical data reveals that all three organizations were using either risk management-based "predict-and-plan" or resilience-based "monitor-and-react" approaches dominantly to manage the unknown risks and surprises in PD projects. Based on the data analysis, we conclude that risk management-based "predict-and-plan" and resilience-based "monitor-and-adapt" approaches complement each other for managing known and unknown risks. The analysis of the empirical data also reveals that the risk management-based "predict-and-plan" approach is an established approach. In contrast, the resilience-based "monitor-and- react" approach is less established in the companies studied to handle surprises in the design process.

4.2.4 Brief Reflection on Contributions

Resilience has the characteristics of agility to respond effectively to unforeseen events and robustness to absorb process variations. Risk management in the PD process contributes to robustness only because it involves proactive planning to avoid process variation. Contrarily, risk management lacks agility because it primarily plans according to known risks with known probabilities. So, its contribution to make the PD process more resilient is limited. Therefore, the PD process requires a more overlapped resilience-focused approach with risk management as well. This paper appears to be one of the first exploratory empirical study of a resilience-inspired approach to PD risk management.

The above results from case company (P1) indicate that the risk management based "predict-and-plan" approach is focused on a proactive measure to avoid risks in the PD process while the resilience-based "monitor-and-react" approach addresses the "reality aspect" of the PD process by reducing the effects of the potential unknown.

The interviews in the other two companies P2 and P3 validate that risk management and resilience complement each other for managing risks in PD projects. Consequently, the PD process needs a more overlapped resilience-focused approach with risk management as well. To generalize the resilience-based PD risk management approach, we propose that further detailed empirical studies need to be conducted.

4.3 Paper C: Planning Unplanned Design Iterations Using Risk Management and Learning Strategies

Table 7 Overview of Paper C

Title	Planning Unplanned Design Iterations Using Risk Management and Learning Strategies
Authors	Ali Shafqat (main author), Josef Oehmen and Torgeir Welo
Aim	The paper explores the utilization of "proactive risk management" and "reactive fast learning" by the product development organizations in a real-world scenario in managing unplanned design iterations.
Research Question	How do organizations employ both 'proactive risk management' approach and 'reactive fast learning' approach to manage unplanned design iterations in the NPD process? (RQ 4 as shown in Figure 1)
Method	A semi-structured interview study was conducted in eight Danish firms in Denmark. The study involved 14 interviewees including CEO, director R&D, project managers, risk managers, and design engineers.
Contribution of the Paper	• Paper C finds that the PRM approach is more established than the RFL approach for managing unplanned design iterations. • The study reveals that the engineering design teams lacked a structured approach to select the most suitable learning methods for resolving the unplanned design iterations after their occurrence. • Observations show that organizations failed to convert the new technical and process knowledge (gained during the resolution of unplanned design iterations) into organizational learning.
Main Author's Contribution	The first author conducted semi-structured interviews and finalized the paper with inputs from co-authors. In addition, co-authors provided input in formulating the RQ and structure of the paper.
Publication Status	Published in *Journal of Engineering Design*, pp.1-24. doi.org/10.1080/09544828.2021.1994531

4.3.1 Brief Description about Unplanned Design Iterations, Risk management, and Learning strategies

Unplanned design iterations are considered one of the reasons for the high failure rate of new product development (NPD) projects. Generally, organizations employ 'proactive risk management (PRM) and 'reactive fast learning' (RFL) to manage unplanned design iterations. This paper explores how organizations employ PRM and RFL approaches to manage unplanned design iterations in the NPD process. To that end, we conducted a cross-sectional interview study in eight organizations. The interview transcripts were analyzed as a primary data source using the thematic qualitative text analysis technique. To explore PRM and RFL approaches' practices, this paper investigates the research question as follows: How do organizations employ both a "proactive risk management" and a "reactive fast learning" approach to manage unplanned design iterations in the NPD process? This paper answers research question 4, as given in Figure 1.

4.3.2 Main Results from the Interview Study

Proactive Risk Management (PRM) Approach

- This empirical study revealed that while utilizing PRM, the engineering design teams maximized their focus on identifying and mitigating the unplanned design iterations risks. They managed this traditionally in the conceptual phase and informally in the design phase of the NPD process.
- The data analysis revealed that the design teams could not identify few unplanned design iteration risks in the conceptual phase of the NPD process.
- This study also showed that the risk monitoring phase identified most of the foreseen unplanned design iteration risks, which were missed in the risk assessment phase.
- The triggers of unplanned design iterations identified during the study were predominantly changing requirements, lack of knowledge, and human errors.

- While employing RFL, the engineering design teams used various learning methods to quickly resolve unplanned design iterations (after their occurrence), specifically prototyping, experimentation and simulations.
- The results also indicate that some unplanned iterations occurred despite utilizing risk mitigation strategies.

Reactive Fast Learning (RFL) Approach

- This study indicates that various risk mitigation actions were used to reduce the occurrence of unplanned design iteration risks. However, this paper adds another dimension to risk mitigation actions by reporting the use of "learning methods" as risk mitigation actions to reduce the likelihood of unplanned design iteration risks.
- The findings from this study indicate that the RFL approach is less established and structured than the well-established PRM approach for managing unplanned design iterations.
- Apart from one organization in the study, the findings from our study demonstrate that organizations, in general, lacked a structured approach to capture the new knowledge, including process and technical knowledge, while resolving the unplanned design iterations.
- Our study also reveals that companies are overall better in single-loop learning as compared to double-loop learning.

4.3.3 Contributions to Answering Research Question 4

For exploring the practices of 'proactive risk management' PRM and 'reactive fast learning' (RFL) for managing the unplanned design iterations by product development organizations, we investigated the research question: How do organizations employ both PRM approach as well as RFL approach, to manage unplanned design iterations in the NPD process?

As an answer, we presented empirical findings on how organizations manage unplanned design iterations using PRM and RFL approaches. The most distinguished finding from this empirical study is that the RFL approach is less established than the well-established PRM approach for managing unplanned design iterations. For the PRM approach, results demonstrate that the design teams were more active in risk monitoring in the design phase than risk identification in the concept development phase. Generally, design teams reduced the likelihood of unplanned design iteration risks by employing learning methods in addition to risk mitigation strategies. The study shows that PRM is a well-established approach for reducing the likelihood of unplanned design iterations using traditional risk management.

For the RFL approach, results of the empirical study revealed that organizations lacked a structured approach to select suitable learning methods for fast resolution of unplanned design iterations. Furthermore, the organizations also lacked a structured approach to convert new knowledge (gained during the resolution of the unplanned design iterations) into organizational learning. Therefore, from an industrial perspective, the PRM approach performed better than anticipated (in the literature) for identifying unplanned design iteration risks except for a few re-occurring risks in the design phase.

4.3.4 Brief Reflection on Contributions

Managing unplanned design iterations is an enormously important intervention for all organizations involved in NPD projects. Our study finds that design teams must manage unplanned design iterations efficiently. This includes minimizing the likelihood of unplanned design iteration risks (using the PRM approach) and the likelihood of the adverse effects after their occurrence by their fast resolution (using the RFL approach). This empirical study suggests that, while employing the RFL approach, it is essential to consider the most efficient learning methods (as explained in appended Paper C) according to the categories of unplanned design iterations. This study also suggests that it is vital to secure new knowledge and use it in future NPD projects through organizational learning to avoid unplanned design iteration in future NPD projects.

Based on Paper C's findings, future research should first outline a structure to select the most efficient learning methods for resolving unplanned design iterations. Second, future research might study why engineering design teams are more active in monitoring unplanned design iteration risks in the design phase than in the NPD process's concept development phase.

4.4 Paper D: Empirical Investigation on the Role of Risk Mitigation Actions in Engineering Projects

Table 8 Overview of Paper D

Title	Empirical Investigation on the Role of Risk Mitigation Actions in Engineering Projects
Authors	Ali Shafqat (main author), Josef Oehmen, Torgeir Welo and Geir Ringen
Aim	This paper explores the utilization of mitigation actions for risk treatment in a real-world scenario of engineering product development organizations.
Research Questions	(1) How do organizations employ risk mitigation actions for risk treatment in NPD projects? (2) Is there a significant difference in utilizing risk mitigation actions in the context of the waterfall and agile methods in NPD projects? (RQs 5 and 6 as shown in Figure 1)
Method	Survey data analysis was conducted using statistical methods.
Contribution of the Paper	• Paper D indicates that the classification of risk mitigation actions in the statistical analysis was in line with the literature-based questionnaire. • Paper D reveals a surprising finding indicating that the individual risk mitigation actions showed significance with the impact of various types of NPD project risks. • Paper D shows that all the selected risk mitigation actions from survey data collectively showed explanation power for treatment, in some way, to the project risks. • Paper D did not find a significant difference in utilizing risk mitigation actions in NPD projects which use waterfall, agile, or both methods.
Main Author's Contribution	The first author conducted survey data analysis using data science techniques. All co-authors provided feedback in RQ formulation, data analysis, and writing of the article. In addition, a co-author (J. Oehmen) conducted the survey.
Publication Status	Paper D is under second review in *Systems Engineering* Journal (submitted on July 12th, 2021).

4.4.1 Brief Description about Risk Mitigation Actions in New Product Development Process

Engineering-based NPD projects face unplanned design iterations, which can be understood as the occurrence of a specific category of engineering project risks. As a result, companies employ structured risk mitigation actions to mitigate these risks. However, even with the employment of mitigation actions, projects still struggle to achieve their targets.

To our knowledge, the literature does not show adequate empirical investigations of how organizations employ risk mitigation actions in compliance with the risks in NPD projects. Therefore, this study explores how companies employ mitigation actions to manage risks in engineering-based NPD projects. For this purpose, we asked two research questions: (1) How do organizations employ risk mitigation actions for risk treatment in NPD projects? (2) Is there a significant difference in utilizing risk mitigation actions in the context of the waterfall and agile methods? We analyzed results from a literature-based survey in the aerospace and defense industry to answer the research questions using data science techniques (see Section 2.2.4 for details). This paper answers research questions 5 and 6, as shown in Figure 1.

4.4.2 Main Results from the Survey Data Analysis

- The statistical data analysis reveals that the classification of risk mitigation actions was in line with the literature-based questionnaire (see appended Paper D for details).
- Surprisingly, the individual risk mitigation actions showed significance with the impact of various NPD project risks in the statistical data analysis.
- The statistical data analysis showed that all the selected risk mitigation actions (from survey data) collectively showed explanation power for treatment, in some way, to the NPD project risks.

- The statistical analysis of the survey data did not find a significant difference for utilizing risk mitigation actions in NPD projects when using waterfall, agile, or both methods.

4.4.3 Contributions to Answering Research Question 5 and 6

This paper aimed to explore how companies employ risk mitigation actions to manage risks in engineering-based NPD projects.

In answer to the first research question, statistical analysis showed that the classification of the risk mitigation actions resembled the literature-based survey questionnaire. In addition, the statistical analysis of the individual risk mitigation actions confirmed that categories of risk mitigation actions are independent of other categories of mitigation actions included in the survey questionnaire (see appended Paper D for details). Further, all risk mitigation actions showed explanation power to mitigate risks in the survey data. In summary, the results of the empirical study reveal that companies employed proactive approaches by employing multiple risk mitigation actions to treat risks.

Surprisingly, concerning the second research question, the statistical analysis did not show a significant difference in utilizing risk mitigation actions in NPD projects employing agile or waterfall or both NPD methods.

4.4.4 Brief Reflection on Contributions

The findings of this empirical study suggest that companies should consider all types of risk mitigation actions (identified in the survey data analysis) to manage NPD project risks. Therefore, contextualizing the suitable risk mitigation actions should be considered while planning the risk mitigation strategies in engineering-based NPD projects.

The data analysis did not show a significant difference in risk mitigation actions when using waterfall or agile (or both) methods. It could be argued that the project managers might have followed traditional risk management practices (as performed in waterfall) irrespectively of the NPD methods due to a lack of integration of risk management in agile NPD methods.

Other researchers should repeat this study using an interview-based detailed qualitative study to validate the current findings for future work. The qualitative validation would add strength to the accuracy of the current findings.

5. Discussion

5.1 Answering the Research Questions

This section discusses the six sub-research questions set out in the introduction section to answer the main research question of the thesis. The six research questions are as follows:

1) What are the learning methods in product design?
2) How can we describe the cost of learning in product design?
3) Do risk management and resilience-based approaches complement each other in managing risks of product development projects?
4) How do organizations employ both the ‘proactive risk management’ approach and ‘reactive fast learning’ approach to manage unplanned design iterations in the NPD process?
5) How do organizations employ risk mitigation actions for risk treatment in NPD projects?
6) Is there a significant difference in utilizing risk mitigation actions in the context of the waterfall and agile methods in NPD projects?

Borrowing from and building on the discussion sections of the appended papers (A, B, C, and D). The following subsections go through each one of these research questions in detail.

5.1.1 Answering Research Questions 1 and 2

We conducted a literature review to conceptualize the cost of learning and explore the learning methods in product design (see appended Paper A). In reviewing the literature, we found insufficient data on the relation between cost and learning in the PD process. In Paper A, **the literature analysis reveals that the cost of learning due to failures and mistakes in PD processes is not well defined** (Beauregard, 2015). However, **our analysis of the literature conceptualizes the cost of learning from failures and mistakes as time and money in the form of time and cost overrun in the**

PD process (Henshall et al., 2017; Smite and Solingen, 2016; Del Río et al., 2014; Drupsteen & Guldenmund, 2014; Lilly & Porter, 2003; Kessler et al., 2000; Postrel, 2002).

The literature review also indicates that **the cost of learning depends on the type of learning task** (e.g., new tasks or tasks based on previous knowledge) (Henshall et al., 2017; Un and Rodríguez, 2018). For example, the cost of learning increases if the engineering design teams do not have prior experience in resolving similar design challenges.

The literature review confirms that **individuals (design engineers) and teams (engineering design teams) are the main classifications of learners in PD processes** (Leifer and Steinert, 2011; Nonaka and Takeuchi, 1996; Leonard-Barton, 1995). The organizational learning theory proposed by Argyris and Schon (1974) also agrees that individuals and teams are the sources of learning in organizations.

We observed that **design teams learn in formal and informal ways** to find the solutions to design challenges in the design phase of the PD process (Leifer and Steinert, 2011). Therefore, **learning methods are divided into two categories, formal and informal**. The identified learning methods during the literature analysis are shown in Table 4. The identified learning methods are suitable in specific situations (Henshall et al., 2017); for example, an appropriate learning method for resolving technology-related design challenges might be prototyping. In comparison, PD projects with low technology risks might not need prototyping. Therefore, it can be assumed that selecting a suitable learning method can affect the cost of learning from an engineering design perspective. Based on these findings, the organizations can formulate a structured approach for selecting appropriate learning methods to reduce the cost of learning.

This literature review provides the theoretical foundations for further empirical research on managing unplanned design iterations. In particular, Paper C explored the utilization of learning methods for fast resolution of unplanned design iterations.

5.1.2 Answering Research Question 3

We conducted an exploratory interview-based case study to investigate risk management and resilience-based approaches in the PD process (see appended Paper B). For this exploratory study, we used the concept suggested by Aven (2019) as a theoretical lens for risk management and resilience. According to Aven (2019), **risk management and resilience to manage known and unknown risks complement each other**.

The results indicate that in the case company (P1), **the engineering teams applied both "predict-and-plan" and "monitor-and-react" approaches** (Paper B). The "predict-and-plan" approach using risk management is focused on proactive measures to avoid risks in the PD process (Herrmann, 2015), while the resilience-based "monitor-and-react" approach addresses the "reality aspect" of the PD process by reducing the effects of the potential unknown risks in uncertain PD environment (Holling, 1973). The analysis of the interview data from all companies indicates that **risk management and resilience complement each other in managing the project risks** (see appended Paper B for interview results).

The results indicate that **the "predict-and-plan" approach was more established in the PD process than the "monitor-and-react" approach** (Paper B). However, there should be more overlap between resilience and risk management approaches to manage known and unknown risks. Resilience has the attributes of (a) agility, which is to respond effectively to unexpected events and (b) robustness, which is to absorb process variations (Aven, 2017; Bhamra et al., 2011; Oehmen and Seering, 2011).

Whereas, risk management in the PD process lacks (a) agility because it generally plans according to known risks with known probabilities and contributes to (b) robustness (only because it entails proactive planning to avoid process variation from known risks). Consequently, **the contribution of risk management to make the PD process more resilient is limited** (Aven, 2019; Oehmen and Seering, 2011). Furthermore, the interview data revealed that **all companies predominantly employed either "predict-and-plan" approach or "monitor-and-react" approach**. Therefore, the PD process demands a more resilience-centered approach with risk management to better manage known and unknown risks.

5.1.3 Answering Research Question 4

We conducted a cross-sectional interview study to explore the management of the unplanned design iterations in the NPD process using "proactive risk management" (PRM) and "reactive fast learning" (RFL) approaches (see appended Paper C). First, we discuss the results for the employment of the PRM approach. We found several insights from the analysis of the interview data that were consistent with the past research. The results demonstrate that **engineering design teams,** while employing the PRM approach, were **generally focused on identifying unplanned design iterations and afterward mitigating them in the concept development phase and the design phase of the NPD process** (Wynn et al., 2007; Meier et al., 2007); **the PRM approach could not identify few unplanned design iteration risks**; and the interview data analysis reveals that **engineering design teams mainly found triggers of the unplanned design iteration under the category of human errors, lack of knowledge, and changing requirements** (Eppinger, 2001; Krehmer et al., 2009; Mujumdar and Maheswari, 2018; Unger and Eppinger, 2011).

As mentioned in the theoretical background (Section 3.1), previous studies have emphasized early detection of potential design iterations in the concept development phase of the NPD process (Wynn et al., 2007; Meier et al., 2007). While using the PRM approach, the interview data analysis also revealed that **engineering design teams focused on forecasting unplanned design iteration risks** (Paper C). This study (Paper C) adds to this view to **acknowledge the need for 'active' risk monitoring**. The active risk monitoring in the detailed design phase might increase the likelihood of predicting unplanned design iterations before their occurrence. For example, the design teams showed more ownership to the risk monitoring in later stages of the NPD process than risk identification at the start of the project.

Previous studies indicate that the risk assessment phase has a limited capability to identify all the known risks (Thamhain, 2013; Beauregard, 2015). In contrast, overall, the data analysis revealed that **the PRM approach performed better in identifying unplanned design iteration risks**, except for a few re-occurring risks in the design phase. In addition, the data analysis of the interview data reported that the **risk monitoring phase identified most of the missed risks in the risk identification phase**. One possible interpretation of this can be that risk identification might be more convenient for design teams due to more information and less uncertainty in the design phase.

Now, we discuss the results related to the employment of RFL in the NPD process from a real-world scenario. While using the RFL approach, the engineering design teams used various learning methods to resolve unplanned design iterations quickly. The **primary learning methods employed after the occurrence of the unplanned design iterations include simulations, prototyping, and experimentation** (Paper C).

In the theory of single-loop learning and double-loop learning, Argyris and Schön (1997) highlighted the significance of using learning and capturing new knowledge for the progress of future NPD projects. However, the data analysis indicated that the **organizations we studied generally lacked a systematic or structured approach to capture the new process and technology-related knowledge** (gained while resolving the unplanned design iterations) (Paper C).

The interview data analysis revealed that **organizations performed better in practicing single-loop learning than double-loop learning** (Paper C). One possible explanation might be that engineering design teams lacked the motivation or incentives to report new knowledge. As a result, the engineering design teams might consider registering the new knowledge as an extra burden and focus on their technical tasks. Another possible interpretation might be that the organizations did not secure enough resources in the project budget to establish a reporting system for capturing new knowledge.

The data analysis disclosed several additional issues that influence the management of unplanned design iterations. Specifically, **organizations we studied lacked a structured approach for selecting suitable learning methods for fast resolution of unplanned design iterations** (Paper C). In addition, **several study participants emphasized the exploitation of learning methods** (along with other risk mitigation actions) to mitigate unplanned design iteration risks before their occurrence. Moreover, **organizations generally did not apply most of the risk assessment tools** recommended in ISO standards (IEC 31010, 2019).

5.1.4 Answering Research Questions 5 and 6

In Paper D, we explored the planning aspect of the risk management process for mitigating NPD project risks (Paper D). To investigate the use of risk mitigation actions, we analyzed the survey data conducted in six US-based aerospace and defense organizations. We used statistical methods (see Section 2.2.4 Analysis of the Survey Data) to analyze the data for investigation of the risk mitigation in NPD projects.

First, we discuss research question number five about organizations' utilization of risk mitigation actions in their NPD projects. We gained insights that were consistent with past research related to risk mitigation actions in the NPD process. For example, previous studies on risk mitigation actions have classified the risk mitigation actions into various risk mitigation strategies (Persson et al., 2009; zur Muehlen and Ho, 2005). This statistical analysis (using cluster analysis) also confirmed that **the classification of risk mitigation actions in survey response** (see Section 4.1 of appended Paper D for statistical analysis results) **was found in accordance with the literature-based questionnaire** (see Table 8 in appended Paper D).

For example, in the survey questionnaire, the risk mitigation actions were classified into four groups. These four risk mitigation groups are as follows: (1) mitigation actions to reduce risks regarding general project management efficiency, (2) mitigation actions to reduce risks regarding requirements, (3) mitigation actions to reduce technological risks, and (4) mitigation actions to reduce risks regarding organizational efficiency. It implies from this finding that project managers might choose risk mitigation actions in the context of NPD projects.

Previous literature has also referred to the significance of tailoring risk mitigation actions according to the background of the NPD projects (Oehmen et al., 2014; Škec et al., 2012; Grubisic et al., 2011). **This statistical analysis supports the previous studies, indicating that the project managers should choose appropriate risk mitigation actions from all four groups of risk mitigation actions in accordance with the contextual factors of the NPD projects**. For example, project managers might tailor risk mitigation action according to the type of the NPD methods (Bassler et al., 2011; Unger and Eppinger,2011), the class of risks identified, and the kind of innovation (ISO, 2018; Oehmen et al., 2014; Škec et al., 2012; Grubisic et al.,2011). Failing to consider risk mitigation actions from all four groups in risk mitigation planning may lead to failure to achieve NPD project targets (Kaplan and Miles, 2012).

The literature shows (Oehmen and Rebentisch, 2010) that organizations encounter challenges in managing significant risks due to the lack of money, human resources, time, or other resources. The statistical analysis also revealed that although project managers employed several risk mitigation actions for managing identified risks, **few identified risks could not get the attention of the project managers for their treatment**. The possible explanation for this inconsistency might be prioritizing the resources for risk mitigation actions, individual project managers' priorities for risk mitigation actions, or organizational culture of risk aversion.

Finally, we used statistical analysis to investigate research question number six. We analyzed survey data to explore risk mitigation actions in three groups of NPD projects employing agile or waterfall or both NPD methods. However, the **survey data analysis did not find a significant difference in practices of risk mitigation actions between three NPD project groups** (see Table 8 of appended Paper D for analysis results). Furthermore, a previous interview-based empirical study has stated no significant difference in project risk management practices using waterfall or agile methods (Siddique and Hussein, 2014).

The possible explanation of this finding might be that project managers generally utilized traditional risk management practices in agile methods (as practiced in the waterfall method) due to the lack of integration of risk management for the former (Siddique and Hussein, 2014). However, previous empirical studies have also found that NPD projects (using agile methods) usually lack traditional risk management practices, e.g., risk identification, risk assessment, and mitigation planning (Kolatch and Henry, 2020; Tomanek and Juricek, 2015; Shrivastava and Rathod, 2015).

Previous empirical studies indicate that although agile methods tend to mitigate risks in the NPD process, however, tailoring the risk management practices is needed from the perspective of agile NPD methods (Shrivastava and Rathod, 2015; de Souza et al., 2021). Furthermore, the current statical analysis of the survey data also **confirms the need for tailoring the risk management process according to agile methods.**

5.2 Reflections on Implications for Industry and Practitioners

A detailed description of implications for industry and practitioners has been discussed in Papers (A, B, C, and D) and this thesis's discussion section above (Section 5.1). Here, we present the implications for industry and practitioners.

1) The learning methods identified in this thesis can guide practitioners in the engineering design phase for the fast resolution of the design challenges or unplanned design iterations. In addition, practitioners can involve risk assessment for early anticipation of design challenges and employ suitable learning methods according to the anticipated situation.

2) The findings of this study suggest that practitioners may fail to manage unplanned design iterations (efficiently) after their occurrence without implementing a structured approach to choose the most efficient learning methods (which are identified in Paper A).
3) The findings (from Section 4.2) indicate that combined risk management and resilience deployment may optimize the NPD process's capability of agility and robustness (see Section 5.2 for details). Therefore, this will assist practitioners in preparing for a better response to known and unknown risks in NPD projects.
4) The findings of the thesis about the practices of risk management and resilience allow practitioners to overlap both approaches in the NPD process.
5) The empirical study (see Section 4.3) of this thesis encourages practitioners to use efficient learning methods (identified in this thesis) for fast resolution of the unplanned design iterations (after their occurrence).
6) Based on the findings (see Section 4.4), practitioners are suggested tailoring the risk management practices corresponding to the type of NPD methods (e.g., waterfall or agile methods).
7) The analysis results suggest that practitioners should consider a variety of risk mitigation actions when planning risk mitigation actions in the NPD process.

5.3 Limitations

This section describes the limitations based on the appended papers and incorporates text from the papers' limitation sections.

5.3.1 Limitations in the Literature Review Study for Conceptualizing the Cost of Learning

The literature review on conceptualizing the cost of learning and learning methods did not include the research papers, which mainly addressed organizational learning and knowledge management in PD projects. The most important limitation of the literature review was that we reviewed the literature about engineering knowledge-based physical product development projects only. We did not focus on medicine- and software-related PD projects. Despite this limitation, the findings could add to the understanding of different aspects of learning in the design phase of the PD process.

5.3.2 Limitations in the Interview Study for Exploring Resilience, Risk Management and Learning Strategies in NPD Process

Several limitations affect the findings of the interview studies conducted in this thesis and must be deemed for future research. First, the interview studies were conducted primarily in the engineering companies, which might be extended to a broader context. Second, the interview studies were conducted in the organizations only headquartered in Denmark. The narratives of resilience, risk management, and learning practices in managing unplanned design iterations and NPD project risks are likely affected by certain Danish cultural aspects. Therefore, this fact might limit the generalizability of the results in this thesis. Third, the interview studies might have been affected by our bias intuitively, e.g., through questionnaire formulation, pushing specific aspects of the study during interviews, or sample selection. The same question was asked in different ways to avoid socially desired answers. However, the respondents might have given biased answers for unknown reasons as in any interview study expected.

5.3.3 Limitations in the Survey Study for Exploring the Role of Risk Mitigation Actions for Managing Risks in Engineering Projects

Several limitations affect the interpretation of the results from the survey study and offer an opening for future research. First, the analysis of the survey data is based on self-reported data that might be biased by the survey respondent's experience. Second, the survey response duplicates the respondents' opinions, which could not be the actuality of the project. Although, a preliminary check was conducted to avoid bias in the survey analysis due to various factors (e.g., type of industry, project size, and respondents' role), which indicated no noticeable impact of any particular group. However, still there exist a possibility for self-selection bias by respondent where the choice to respond or avoid the survey might be influenced by the respondent's strong views about risk management practices. Finally, the data sample of the survey was composed of large defense and aerospace organizations. Therefore, this might limit the application of findings and their generalizability in a larger industrial context.

6. Overall Conclusions

This section presents major contributions of the sub-research questions based on the appended papers (A, B, C, and D).

6.1 Research Findings and Contributions

Contribution 1: Answering Research Questions 1 and 2 - What are learning methods in product design? How can we describe the cost of learning in product design?

To address the first two sub-research questions, in Paper A, we aimed to define the cost of learning from failures and mistakes and identify the learning methods practiced in the engineering design phase by reviewing the literature. Based on the literature analysis, it can be concluded that the cost of learning from failures and mistakes is not well defined in the literature. Few learning methods are practiced to resolve design challenges in the design phase of the PD process. The results indicate that cost of learning can be defined as the conventional cost and time overrun in the PD projects (due to failures and mistakes to resolve the design challenges). Moreover, learning methods can be categorized as formal and informal learning methods.

In this literature review, the most critical limitation is that we did not focus on software-and medicine-related PD projects. Instead, we aimed to review the literature related to engineering knowledge-based physical product development projects. Despite this limitation, these findings could add to understanding different aspects of learning in the product design phase.

Based on these findings, practitioners should consider utilizing appropriate learning methods in combination with risk analysis. The risk analysis process can recognize the design challenges, and design engineers can choose suitable learning methods for resolving design challenges.

Overall, these findings fill the knowledge gap on conceptualizing the cost of learning from failures and mistakes and identifying the learning methods practiced by engineering design teams in the PD process.

Contribution 2: Answering Research Question 3 - Do risk management and resilience-based approaches complement each other in managing risks of product development projects?

In Paper B, we investigated the hypothesis that resilience-based “monitor-and-react” and risk management-based “predict-and-plan” approaches are complementary in PD risk management. Our case study and extra validation interviews confirmed this for the organizations that were studied.

The empirical data analysis concludes that the “predict-and-plan” is an established approach. In contrast, the resilience-based “monitor-and-adapt” approach is less established to handle surprises in the engineering design phase.

After analyzing the empirical data in Paper B and studying the literature, we recommend that by the overlap of the resilience and risk management approaches, the overall immunity of the PD process against known and unknown risks can be increased.

This study happens to be the first exploratory empirical study of a resilience-inspired approach to PD risk management. However, to generalize the resilience-inspired risk management approach in PD projects, we propose additional empirical studies.

Contribution 3: Answering Research Questions 4 - How do organizations employ both ‘proactive risk management’ approach as well as ‘reactive fast learning’ approach to manage unplanned design iterations in the NPD process?

In Paper C, we presented findings from an empirical study on how organizations employ “proactive risk management” (PRM) and “reactive fast learning” (RLF) in managing unplanned design iterations to answer.

Based on the empirical data analysis, we conclude that the PRM approach reduced the likelihood of unplanned design iterations. At the same time, the RFL approach contributed to lowering the adverse impact of the unplanned design iterations after their occurrence. The empirical data analysis also concludes that the PRM approach is more established than the RFL approach.

After analyzing empirical data, we recommend that practitioners establish an approach for selecting the most suitable learning methods to manage unplanned design iterations. Moreover, they should convert technical and process-related knowledge (acquired during the resolution of unplanned design iterations) into organizational learning.

Contribution 4: Answering Research Questions 5 and 6 - How do organizations employ risk mitigation actions for risk treatment in NPD projects? Is there a significant difference in utilizing risk mitigation actions in the context of the waterfall and agile methods in NPD projects?

Paper D addresses research questions five and six. We analyzed the survey data conducted in six US-based aerospace and defense organizations by applying statistical methods to answer the research questions. To answer the fifth research question, we presented survey-based findings of utilizing risk mitigation actions for managing risks by engineering organizations in a real-world scenario.

We conclude from the statistical analysis that despite their categorization, all the identified risk mitigation actions in survey data generally contributed to mitigate various types of risks. Furthermore, from the survey data analysis, we conclude that (surveyed) organizations employed multiple risk mitigation actions to treat their NPD project risks. The employment of multiple risk mitigation actions indicates that organizations used a risk management-based “predict-and- plan” approach to managing NPD risks.

To investigate the sixth research question, we presented empirical findings of using mitigation actions in engineering-based NPD projects employing the waterfall, agile, or both methods. After analyzing the survey data, we conclude that organizations using different NPD methods (waterfall, agile, or both) did not significantly differ in how they engage the risk mitigation actions.

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Part II: The Appended Research Papers

Paper A - The Cost of Learning from Failures and Mistakes in Product Design: Reviewing the Literature

The 22nd International Conference on Engineering Design (ICED 19)

THE COST OF LEARNING FROM FAILURES AND MISTAKES IN PRODUCT DESIGN: REVIEWING THE LITERATURE

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ABSTRACT

In the design phase of product development (PD) process, most new products face significant uncertainties and risks. Uncertainty is typically associated with a lack of information, while learning is a process that acquires information. Therefore, learning fast and at a low cost decreases the uncertainty and increases the efficiency of the product design phase. This paper investigates the concept of the cost of learning in PD's design phase. Reviewing the literature, we conceptualize the cost of learning and review the learning methods considering three aspects in the design phase of the PD process: (1) costs associated with learning from mistakes and failures, (2) learning methods, and (3) categories of learners. This paper thus provides the conceptual foundations for future work to increase the efficiency of the PD process by reducing the cost of learning from mistakes and failures.

Keywords: Design learning; Design costing; New product development; Uncertainty; Design methods

1. Introduction

Today's organisations strive to achieve technological advancements and growth. To have an advantage over competitors, organisations must innovate new products or improve existing products. In this regard, companies must strive to optimise cost, quality and lead time (Oehmen et al. 2010, Chauhan et al. 2017).

At the same time, new product development (NPD) projects are becoming more complex as they become more unique and as more requirements change due to dynamics in the market. Hence, the NPD process faces significant risks, including technical risk, financial risk, collaboration risk, regulatory risk, schedule risk and market risk (Awny 2006, Unger and Eppinger 2009, Wu and Wu 2014). Moreover, in the early phases of NPD projects, there are more risks and uncertainties (Lough et al. 2009) due to lack of information. The literature demonstrates that current product development methods are not fully capable of addressing these additional challenges (Oehmen et al. 2014, Schuh et al. 2017). Therefore, many NPD projects fail during their development processes or soon after they are in the market (Barczak et al., 2009).

To solve design problems, NPD teams learn from failures and mistakes (Drupsteen & Guldenmund, 2014; Kolb, 2014). To improve current and future projects, teams and individuals use the learning outcomes of efforts to solve design problems in the design phase. As a result, the costs of learning related to solving issues in NPD are the utilised resources, such as time and money, and sometimes product failure. Therefore, the overall product development process becomes expensive and less productive.

The success of NPD projects directly affects the growth and profitability of the organisation. Yet the success rate of the new products is disappointing. One study reveals that only 15% of new ideas for products and around 60% of NPD projects achieve commercial success in the market (Barczak et al., 2009). Another study (Gourville, 2006) shows that the failure rate of new products can reach 90%. In the majority of the cases, NPD projects turned out to be costly, and failure was too expensive for organisations in terms of input resources.

There are multiple studies on the lessons learned from mistakes (McClory et al., 2017; Schindler & Eppler, 2003; Stosic et al., 2016); however, to our knowledge, there are few literature reviews on the "cost of learning" and "learning methods" in product design. Therefore, we address the identified literature gap regarding the "cost of learning" in the engineering design phase of the NPD process. This literature review will contribute to a future research agenda for understanding the role of risk mitigation in minimizing the cost of learning and thus the cost of product development. In this literature review, we ask the following research questions:

What are the learning methods in product design?
How can we describe the cost of learning in product design?

The corporate world primarily uses the term "learning" from an organisational perspective (Senge, 1991). There is also a trend in the academic community to study learning in connection to NPD (Akgün et al., 2006; Cui et al., 2014; Lynn et al., 2003; Lynn et al., 1996; Un & Rodríguez, 2018). We take the definition of learning as "processes of information or knowledge acquisition, distribution, interpretation and storage" (Schulze et al., 2013). The product design phase plays the main role in defining the physical form and function of the product. The design phase includes various activities from, for example, the areas of industrial design (user interface, aesthetics, and ergonomics) and engineering design (mechanical, electrical, software, etc.) (Ulrich and Eppinger 2015). This paper focuses on learning in engineering design teams. Therefore, we limit the scope of this paper to the context of learning in engineering design.

This paper contributes to the existing research on this subject in two ways. First, this paper provides an overview of the types of learners, learning methods and the costs associated with learning in the NPD design phase. Second, this paper contributes to the understanding of the link between the cost of learning and learning methods. This paper provides a conceptual framework for future research aimed at integrating the three separate streams of research: organisational learning, risk management and NPD.

The structure of the remaining paper is as follows. Section 2 describes the research methodology and details about the literature search and analysis. Section 3 provides an overview of the results of the literature search. Section 4 discusses the results, in order to improve the NPD process from a learning perspective. Section 5 concludes the discussion and briefly explains the potential for future research.

2. Method

To create an overview of the literature, we used the Scopus and Science Direct databases. Our searches focused on the titles, keywords and abstracts of the peer-reviewed papers without limiting the search to specific dates of publication. We reviewed English language papers only and used Boolean operators (OR and AND) in the search strings. The following search strings were used: ("product development process" AND learning), ("product design" AND "learning cost"), ("product development process" AND "learning" AND "cost") and ("innovation" AND "learning cost"). We excluded the fields of "nursing", "health care" and "medicine". We did not focus on additional searches for topics about knowledge management and general learning in projects. The initial searches with the aforementioned search strings in Scopus (339) and Science Direct (273) produced 612 references. The initial scanning of the titles produced 49 relevant research articles for closer review. After scanning the abstracts and the introduction and conclusion sections, we excluded 30 papers since these papers primarily addressed organisational learning and knowledge management in NPD projects. We studied the remaining 21 articles in detail and identified nine additional articles after backward referencing. To answer the research questions in this paper, we therefore reviewed 30 articles in total.

3. Learning in Product development process

In connection with the topic of learning in the NPD process, we adopt the definitions of the single-loop and double-loop learning theories by (Argyris & Schon, 1974). According to (Argyris & Schön, 1997), when the error detection and correction process permits the organisation to follow its present policies, this process is called single-loop learning. Double-loop learning takes place when the error detection and correction process questions and modifies the organisation's underlying policies and objectives. The design teams learn from failures and mistakes and improve the design. We can describe single-loop and double-loop learning with an example from NPD projects. In the detailed design phase of NPD projects, the design teams make efforts to achieve the design requirements. In this design process, designers face problems to achieve the set design goals. To solve the design problems, designers change their approach and acquire the appropriate knowledge. This is the example of a single-loop learning process in an NPD context. Another example of what is meant by double-loop learning is to change the set requirements of the NPD project by taking feedback from design and marketing teams. Hence, the management learns from mistakes and learn in order to improve the next NPD projects.

3.1 Costs of learning

Kessler et al. (2000) studied 75 NPD projects to investigate the influence of technology sourcing strategies on innovation speed, development cost and competitive advantage. The results of the study demonstrate that more technology sourcing lowers competitive success and increases development costs. Outsourcing in the technology development phase of an NPD project significantly increases project completion time. Therefore, we can conclude that learning through outsourcing in design teams can increase the development time and cost of NPD projects. Smite and van Solingen (2016) conducted a study on software-based product development scenarios. They conclude in their study that the cost of learning due to outsourcing outside the company was more than the hourly cost of in-house learning. In the end, they find it less expensive to learn within the company. Therefore, we can infer that the cost associated with learning from outsourcing is more than in-house learning. Lilly and Porter (2003) argue that improvement reviews of the NPD process can be a step to enhance learning in NPD process. These reviews serve as inputs that help teams prioritise the best-suited learning agenda for solving design problems. Therefore, design teams can use lessons learned from previous product development projects as an input that helps them identify the design issues with greater impact on project costs. Therefore, the quicker the response to the problems identified in the review process, the lower the cost of learning. We can conclude that (lead) time is another factor associated with the cost of learning. Likewise, Postrel (2002) claims that the learning tasks with previous knowledge have lower learning cost as compared to completely new learning tasks.

Del Río et al. (2014) point out that virtual experiments, such as CAD models in the design phase, can reduce the development time and cost of learning in the product development process. Thus, development time and money can be identified as the cost of learning in the design phase of NPD projects. Similarly, Henshall et al. (2017) identify design rework as a cost factor that engineering design teams can reduce with learning interventions that develop the skills of the engineering teams. Therefore, we can identify the cost of design rework as one type of learning cost.

Drupsteen and Guldenmund (2014) conducted a literature review and defined learning from incidents and accidents based on the results of the events that have occurred. Therefore, we can conclude that the costs of learning in these scenarios are the failures of the designs or the mistakes in the design phase.

The evidence presented in this section suggests that the cost of learning can be classified as time and money. The results from current section are discussed in section

3.2 Categories of learners

Saban et al. (2000) categorise learners in the product development process as learners in level 1 and level 2. Level 1 participants, in single-loop and double-loop learning, are typically design teams and designers. Level 2 learners are at a strategic level and are the ones that establish business goals.

Observations and investigations in the field of organisational learning have revealed that teams are the fundamental source of learning in organisations (Leonard-Barton, 1995; Nonaka & Takeuchi, 1996; Senge, 1991). Leifer and Steinert (2011) also agree in their study that product development teams learn in the design and development process. Most of the papers cited by Leifer and Steinert (2011) categorise learners in the product development process as teams and individuals. Overall, the evidence presented in this section suggests that teams and individuals are the two main categories of the learners in engineering product development.

3.3 Measures of learning in the product development process

To measure the learning and cost associated with repetitive tasks, Anzanello and Fogliatto (2011) review the literature on learning curves. The concept of learning curves can also be used in the product development process to measure the learning capability of design teams and individuals (Anzanello & Fogliatto, 2011). In contrast, as product development is not a repetitive task, it is difficult to measure the learning capability of design teams and individual designers by implementing the learning curve method. There are many factors (e.g., prior experience and task complexity) that affect the learning capabilities of individuals and design teams (Nembhard & Uzumeri, 2000a, 2000b; Pananiswami & Bishop, 1991). The fields of design learning and design education can be an inspiration for the measurement of learning in engineering design teams. Boylan and Demack (2018) argue that professional learning can be assessed in innovative projects by measuring the improvements in outcomes and assessing the extent to which professional learning occurs. Denson et al. (2015) argue that the Consensual Assessment Technique can be used to measure creativity in engineering design. This method can possibly be an inspiration for measuring the creativity of design teams in solving design issues. They represent web-based adaption of the Consensual Assessment Technique for the evaluation of student projects. The students developed engineering projects during a week-long engineering camp.

3.4 Learning methods in the product development process

Dalmaz et al. (2015) review learning methods from an NPD perspective. They categorise learning methods as either formal or informal methods of learning. McKee (1992) reviews the literature on the organisational learning approach to product development. He relates three learning levels to innovation. Specifically, he relates single-loop learning to incremental innovation, double loop learning to discontinuous innovation and meta-learning (i.e., how to fail intelligently) to institutionalised innovation. Single-loop and double-loop learning occur in specific product development projects and meta-learning helps higher management in learning from experiences in innovation projects. Similarly, Leifer and Steinert (2011) propose that learning in the product development process occur in formal and informal ways. Based on prior work, they identify three learning loops in the product development process. Learning loop one is based on explicit knowledge and it brings product development teams into the formal structure of the organisation. In loop one, the aim of the learning is to retain project knowledge. This loop falls into the category of formal learning. In loop two, learning occurs during exchanges between design teams and coaches. Learning loop two is categorised as an informal way of learning. The third learning loop is also an informal way of learning, and team members learn from each other and prior teams' experiences.

Yuan Fu et al. (2006) identify the knowledge required for teams to make decisions in the product development process, such as market knowledge, human knowledge, technological knowledge and procedural knowledge. Therefore, we can say that knowledge acquisition is an essential part of the learning process in which the appropriate knowledge is acquired and processed. Cui et al. (2014) propose that new information generated during the NPD process is a source of learning. They identify this information acquisition as the learning zone in NPD. The teams in NPD learn from new knowledge generated in the innovation process. Therefore, we categorise this learning method as "learning by doing".

Drupsteen and Guldenmund (2014) review the literature on safety and define learning from incidents within organisations. They compare learning from incidents with organisational learning. This learning method is another way of learning in the product design phase that can be referred to as "learning from mistakes and incidents". Their study also demonstrates that only high impact incidents are used for learning and many opportunities to learn from small incidents are missed due to lack of reporting.

Erichsen et al. (2016) propose a model of four prototyping categories to learn internally and externally in the product development process. They use two case studies from the automotive industry and propose prototypes as a method of learning in the product development process, both internally and externally.

Un and Rodríguez (2018) analyse the influence of research and development outsourcing on product innovation. Outsourcing is another way of learning in NPD projects. Lynn et al. (2003) propose the accelerated learning concept in new product development teams. They argue that fast learning enables product development teams to introduce new products into the market quickly, which can increase the product success rate. They suggest that vision clarity, knowledge gained from customers and competitors, past product reviews and aggressive deadlines can be the ways of learning in the product development process. Likewise, Henshall et al. (2017) argue that learning can enhance the efficiency of the product development process and reduce the cost of design rework. They suggest that efficiency of the product development process can be enhance by defining learning intervention aimed at developing skills in senior engineering management. They propose lectures, training and group work as learning strategies or methods in the product development process.

Henshall et al. (2017) developed a model of learning cycles in the NPD process. They developed three learning methods: (1) "learning by using," which is based on customers' experiences after using the product, (2) "learning by doing," which occurs as the firm manufactures a greater volume of the product and (3) "learning by failures," which takes place as managers identify failure patterns and weak links in the organisation by launching successive generations of the product into market.

D'Este et al. (2017) identify two types of learning mechanisms in exploratory R&D, which they label as "learning from experience" and "inferential-based learning". To reduce the failure rate of NPD projects, it might be possible for design teams to use learning opportunities.

In summary, these results demonstrate that product development teams learn about solutions to design problems using various learning methods. The learning methods identified in the literature are summarised in the next section of this paper.

4. Discussion

Our analysis of the literature demonstrates that the cost of learning due to failures and mistakes in product development processes is not well defined. In reviewing the literature, we found insufficient data (Un & Rodríguez, 2018) on the relation between cost and learning in the product development process. The results of this study indicate that the cost of learning in product development depends on the learners and learning methods (e.g., learning through prototyping or outsourcing). Another important finding of this review is that despite the number of papers written on the subject of learning in the product development process, the initial reviewed papers tend to be more focused on learning in all NPD phases instead of learning in the design phase.

The organisational learning theory proposed by Argyris and Schon (1974) also agrees that individuals and teams are the sources of learning in organisations. There exists another categorisation of learners as level 1 and level 2 learners that is based on the organisational learning theories of single-loop learning and double-loop learning. The results of this study confirm that individuals and teams are the basic categories of learners in product development processes (Leifer & Steinert, 2011; Leonard-Barton, 1995; Nonaka & Takeuchi, 1996).

Table 1. Learning methods

Learning Method	Categories of learning methods	Reference
Learning through knowledge acquisition, training and lectures	Formal	(Yuan Fu, Ping Chui, & Helander, 2006), (Henshall et al., 2017)
Learn by doing	Formal	(Cui et al., 2014), (Henshall et al., 2017)
Learning from incidents and failures	Formal/Informal	(Drupsteen & Guldenmund, 2014), (Henshall et al., 2017)
Prototyping and experiments	Formal	(Erichsen et al. 2016)
Learning from teammates and coaches	Informal	(Leifer & Steinert, 2011)
Outsourcing	Formal	(Un & Rodríguez, 2018)
Past product reviews, customers	Formal	(Lynn et al., 2003)

To solve design issues, design teams face unique challenges and situations in which they learn. The literature to date makes little reference to the question of how to measure learning in engineering design teams. The manufacturing industry primarily uses learning curves to measure learning in repetitive tasks. To measure learning in the product design phase, it is challenging to implement the learning curve methodology because of the non-repetitive nature of the tasks, complexity of the tasks and the learning capability of individuals and design teams. However, Anzanello and Fogliatto (2011) argue that by using the learning curve methodology, design teams can measure the learning involved in the development of products that are similar in terms of configuration. We suggest that the learning ability of design teams can be linked to the time between the detection of the design problem and the time needed to solve the identified problem. However, this time also depends on the complexity of the design problem and the previous experience of the designers. The expected learning time needed to solve the design problems can be longer if the design team does not have previous experience in solving similar design problems detected in the design process.

Table 1 addresses the first research question and illustrates that different learning methods do exist in product design. When focusing on the design phase, we observe that design teams learn in formal and informal ways to find the solutions to design problems. Therefore, we divide the learning methods into two categories, formal and informal, as illustrated in Table 1. The identified methods are suitable in certain situations; for example, when the product is unique and there are market risks, the suitable method for learning about market needs might be "prototyping". In contrast, NPD projects with low market and technical risks might not need prototyping. When the product design has similarities with other product development projects, the past product review can be a suitable method for learning. Therefore, it can be possible to assume that the selection of a suitable learning method can affect the cost of learning from an engineering design perspective.

Table 2, which relates to the second research question, illustrates that the cost of learning can be divided into two categories: time and money. The literature review also indicates that the cost of learning depends on the type of learning task (e.g., new tasks or tasks based on previous knowledge). There is a link between both types of costs of learning (time and money); for example, when the launching time of the product is of primary importance, money becomes the second priority and time is considered as the cost of learning. When NPD projects have limited resources and flexibility in terms of time to market the product, money or development costs becomes the cost of learning. Early in the design process, exploring and prioritising difficult learning tasks can reduce the cost of learning. Similarly, using prototypes and design iterations to acquire customer feedback in the early stages of the product development process can reduce the cost of learning. Therefore, in our opinion, it is possible to learn proactively in the early stages of the product design process by foreseeing potential design problems. By reviewing the literature on the cost of learning due to failures and mistakes in the product development process, we contribute to the knowledge about the cost of learning from mistakes and failures in NPD projects and learning methods. This will help to identify possible explanations for inefficiencies and high costs of learning in the NPD process.

Table 2. Categories of the cost of learning

Cost of learning	Category	Reference
Time overrun due to outsourcing learning	Time	(Kessler et al., 2000), (Postrel, 2002)
Design failure, Design rework	Money	(Del Río et al., 2014), (Lilly & Porter, 2003), (Smite & van Solingen, 2016), (Henshall et al., 2017), (Drupsteen & Guldenmund, 2014)

This literature review also provides the theoretical foundations for further research on increasing the efficiency of the product development process by reducing the cost of learning through risk management. The literature review is limited to a selection of peer-reviewed papers only, whereas there are books that cover different aspects of learning in the product development process.

5. Conclusion

The design phase of the product development process faces unique problems due to uncertainties and risks. Timely information and learning about design problems and solutions tend to reduce the uncertainties and mitigate risks. In many situations, learning from mistakes and incorrect decisions in the design phase is costly. There is a range of studies on individual, team and organisational learning. However, there is a gap in the literature review on the cost of learning in the design phase of the engineering product development process.

The cost of learning is not well defined in the engineering design phase of the product development phase. This paper has defined the cost of learning in the design phase as time and money. Time as the cost of learning is further categorised as time overrun due to outsourcing the learning. Money as the cost of learning is subcategorised into design failure and design rework. The paper has also identified that generally, the categories of learners in the product design phase are individual product designers and design teams. Reviewing the literature, we mainly categorised the learning methods in the design phase into formal and informal learning methods. Learning methods such as learning by doing, prototyping, outsourcing, consulting past product reviews and learning through training and lectures are included in the formal learning methods category. Learning from incidents is included in the informal learning methods category. We find in the literature that the selection of learning methods is claimed to affect the cost of learning. One of the more significant findings emerging from this paper is that to reduce learning costs, risk analysis can be used in the product design phase. The risk analysis process can identify the design problems and design engineers can choose suitable learning strategies for solving design problems.

These findings contribute in several ways to our understanding of the cost of learning in the product design phase. The most important limitation is the fact that we review the literature in relation to engineering knowledge-based physical product development projects. We are not focusing on software- and medicine-related product development projects. Despite this limitation, this paper could add to the understanding of different aspects of learning in the product design phase.

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Paper B - Resilience in Product Design and Development Processes: A Risk Management Viewpoint

29th CIRP Design 2019 (CIRP Design 2019)

Resilience in Product Design and Development Processes: A Risk Management Viewpoint

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Abstract

Product development (PD) faces uncertainties from rapidly developing technologies, shifting market demands and resulting requirements change and the organization's ability to reliably execute state-of-the-art processes. In this paper, we argue that classic PD risk management methods and tools are based on the "predict and plan" paradigm, assuming that we have sufficient time and resources to identify, analyze and mitigate these technology requirements and organizational risks. However, the "reality of product development" is that we usually have neither, and at the same time we are faced with an accelerated introduction of uncertainty, for example by pervasive digitalization. This paper therefore explores a resilience-inspired approach to PD risk management, which abandons the "predict and plan" paradigm in favour of a "monitor and react" approach. We argue that in industrial practice, this is the de-facto risk management baseline, and suggest to deliberately tailor risk management and PD processes accordingly. To that end, we make suggestions for process frameworks and tools and discuss how resilience and risk management are complementary approaches to traditional PD approaches. Our arguments are supported by a case study in an engineering organization, along with additional interviews in similar organizations for validation.

Keywords: Product development; Design methods; Failures; Resilience

1. Introduction

Product innovation is considered one of the major success factors for manufacturing companies [1]. In addition, tough competition puts high pressure on companies to introduce new products to capture new markets. New product development (NPD) processes face significant risks. A study shows that only 15% of new product ideas and around 60% of NPD products achieve commercial success in the market [2]. The success of a NPD project is usually measured by length of lead and development time, cost and ability to satisfy customer demands. NPD projects face risks that can cause cost overrun, time overrun and even failure to achieve the desired product performance [3].

There are different definitions of these risks in the literature; for instance the ISO 31000 defines risk as the "effect of uncertainty on achieving the NPD objectives" [4]. The risks in the product development process (PDP) include technology risks, market risks, collaborative risks and financial risks [5]. It is typically beneficial to address risks and uncertainties during the early design phase of product development (PD) because early assessment of risks can reduce the cost of mitigation efforts, as shown in Fig. 1 below [6]. The risk is very high at the start of a project whereas the cost to fix risk events is very low during the same period, as compared to the later stages, as shown in Fig. 1 below [6]. To mitigate risks in PD projects, risk management is often applied to identify and control the risks in PD projects [4,6]. This approach can be named as "predict and plan" risk management approach.

First, the "predict and plan" risk management approach focuses on maximizing efforts to identfy the risks and quantify the occurance of the potential risks. Second, this approach plan to mitigate the identified risks. For example, risk identification, analysis and assessment are performed in the start of the NPD projects and appropriate risk mitigation measures are planned accordingly [6]. Therefore, risk management processes typically follow a "predict and plan" approach to mitigate risks in NPD projects. However, the literature shows that a vast amount of risk is not identified before they tend to affect the performance [7], or alternatively they are identified but not addressed properly [14].

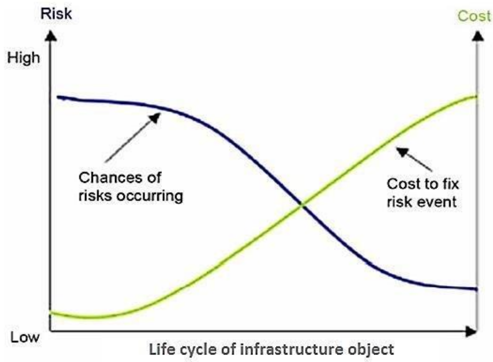

Figure 1 Cost and risks in project lifecycle (adopted from [6]).

Schuh et al. [5] and Oehmen et al. [8] argue that current PD strategies and approaches are not fully capable to address changes in PDP [2,8]. Risks in the PDP are often addressed in a reactive way instead of using proactive risk management strategies [9]. This approach can be named as “monitor and adapt”. For example, the design engineers face unexpected design problems in design phase and they try to find the possible solutions for the unexpected design problems in a short duration. So, the design engineers monitor the situation and try to adapt according to the situation. Aven [10] argues that in general, risk management and resilience management complement each other. He pointed out that resilience analysis and management today is the integrated part of the risk field and science. Therefore, we hypothesize that in general, the capability of the PDP to identify, analyze and mitigate the technology, requirement and organizational risks may be enhanced by introducing resilience-inspired approaches to PD risk management.

Resilience is the capability of a system to sense, recognize, absorb and adapt to the changes, disturbances, variations, surprises and disruptions [11,12,28]. As an approach of PD, the focus of resilience is on retaining ‘post surprise’ options, under the assumption that surprise is inevitable.

The field of resilience is developing at a fast pace and widening its application area, particularly in the contexts of security and infrastructure [10]. In engineering, the concept of resilience was introduced by the safety engineering community [11] which is relatively new as compared to other fields [12]. By enhancing resilience of the system, the safety of the system can be improved without performing risk calculations [10]. In a traditional risk assessment process, it is compulsory to quantify risks, for example by modeling impact-probability distributions. For a resilience approach, that is not strictly necessary [10].

We follow the argument of the Aven [10] to adopt holistic approach integrating risk- and resilience-based thinking. This approach encourages considering both risk management and resilience perspectives as complementary to each other. Following this argument, a risk analysis framework is required to give proper direction to a resilience approach. Moreover, resilience approaches add reactive and adaptive capabilities that are not covered by risk management. We transfer this argument to PD and investigate the potential of combined resilience and risk management approaches to make the PD process more cost effective, fast and technically superior to develop quality products.

The reminder of the paper is organized in the following way: Section 2 explains the research method used to conduct the research. Section 3 describes the standard risk management framework and shortcomings of existing approaches. Section 4 provides perspective of the resilience approach for unknown risks in the PD process. Section 5 presents the findings from a qualitative case study and additional interviews. Section 6 analyses and discusses the co-existence of the classic risk management and resilience in PD projects. Section 7 gives the conclusion.

2. Method

The research nature in this paper is exploratory as we seek to empirically understand and establish the relationship between resilience and risk management in product design and development perspective. The research approach is predominantly deductive [31]. The most suitable research method in this scenario is thus case study [13]. In the case study, we investigate ongoing PD project where we have no control over the environment. The exploratory character of the research makes interview as the primary method of data collection.

Three companies (P1, P2, and P3) provided the data for this research. To conduct case study, company P1 provided access to design team, project documentation, product management and program management. To conduct additional interviews, P2 and P3 companies facilitated access to project managers. All three organizations are large international companies in the medical industry having headquarters in Denmark.

The case study focuses on one product PD project (Project1 in P1) in detail, by conducting interviews with the project managers and design engineers. We also conduct interviews in other two companies to explore the findings beyond the case study itself. Design engineers may have personal views on project success and they have their own role in risk management and resilience. In the case study (P1), we gather additional information through documentation of Project1 for a detailed study. We record and create a complete transcript of all interviews. The duration of the interviews varied from 45 to 60 minutes.

We conducted the semi-structured interviews [31] and strove to achieve consistency and reliability by using the same interview script in terms of topics to address. The interview script is based on the combination of open and closed questions by focusing on three elements: how risk management was performed, why risk management failed to control risks and how resilience-based practices enhanced the capability of PDP to control unknown risks. The analysis is done by means of pattern matching [13]. The coding scheme was developed by reviewing literature on risk management and resilience as presented in the literature review (Sections 3 and 4). We identified instances of “predict and plan” and “monitor and adapt” as well instances of risk management such as risk identification and instances of resilience such as ability to adapt.

3. Risk Management in Product Development

Risk management is known as the process to uncover and manage risk in PDP, following a structured approach by initiating timely mitigation action to avoid, transfer or reduce risk likelihood or impact [15]. Herrmann [16] describes the key steps in risk management processes as follows:

- Risk framing
- Risk identification
- Risk analysis
- Risk evaluation
- Risk treatment
- Risk monitoring and review
- Risk communication

In a risk management process, risk assessment is a critical phase which includes risk identification, risk analysis, and risk evaluation. A risk assessment process provides basis for an improved understanding of the risks and appropriate approaches to be used for risk treatment [30]. The risk assessment process uses appropriate tools and techniques during life-cycle phases of a PD project. For example, during the design and development phase of a PD project, risk assessment contributes to the design refinement process, cost effectiveness studies and enable the system risks are tolerable [30].

The well-known tools and techniques used in risk assessment phase are listed in Table 1 [30]. This table shows the tools and techniques used in the risk assessment phase of the risk management process. The application of the tools and techniques depends on the stage of the risk assessment phase. As Table 1 shows the primary hazard analysis technique is strongly applicable for risk identification but not applicable to analyze and evaluate identified risks. Similarly, in PD projects root cause analysis is not applicable to identify risks but strongly applicable to analyze and evaluate risks.

Keizer et al. [17] found out in their study that traditional risk management techniques are inadequate to control PD risks. The traditional risk management techniques include fault tree analysis, event tree analysis and failure mode and effects analysis as mentioned in Table 1. The tools and techniques in Table 1 are used typically in “predict and plan” approaches. These techniques identify the potential risks in PD projects. The identified risks are analyzed and evaluated to assess for further risk mitigation planning. The draw back for “predict and plan” approach is that project will not be able to control the unpredicted risks in an uncertain project environment. As, Thamhain [7] argues that large number of risks are not predicted in risk assessment phase and these risks affect the project performance in the later stages.

3.1 PDP for products with diverse risk characteristics

There are many risks involved in the PDP, depending on the type of the product chosen for development [18]. The range of PDPs varies from highly rigid and controlled process to very flexible approaches [19,20]. Risks and mitigation strategies in PDP depend on the type of the product, market situation, time and budget. Table 2 shows a summary of general risks involved in PDP that are technical, marketing, schedule and related to budget.

Table 1. Tools and techniques in risk assessment process. [30]

Tools and techniques	Risk assessment Risk identification	Risk analysis	Risk evaluation
Delphi	SA[1)]	NA[2)]	NA
Brainstorming	SA	NA	NA
Check lists	SA	NA	NA
Primary hazard analysis	SA	NA	NA
Hazard and operability studies (HAZOP)	SA	A	A
Root cause analysis	NA	SA	SA
Failure mode effect analysis	SA	SA	SA
Fault tree analysis	A	A	A
Event tree analysis	A	A	NA
Cause and consequence analysis	A	A	A
Cause-and-effect analysis	SA	A	NA
Decision tree	NA	SA	A
Bow tie analysis	NA	SA	A
Monte Carlo simulation	NA	NA	SA
FN curve	A	SA	SA
Risk indices	A	SA	SA
Consequence/probability analysis	SA	SA	A

[4)] Strongly applicable
[5)] Not applicable
[6)] Applicable [30]

The risks listed in Table 2 are major risk categories in PDP, according to Unger and Eppinger [18]. These risks may further be divided into subcategories that become increasingly unique for each company and project [18].

Table 2. Major risk categories in PDP.

Major risks	Causes [21]	Suitable PDP [18]
Technical	Vague design specifications, high in physical product development	Staged process
Marketing	Changing customer needs	Spiral process
Schedule	Lack of planning and coordination among developers	Staged process
Financial	Limited resources, underestimation in budget planning	Design-to budget

4. Resilience in Product Development

The contemporary concept of resilience was proposed by Holling [22] to describe ecological systems, persisting in unpredictable environments. Here, Holling [22] made a fundamental distinction between systems designed for stability and systems designed for resilience.

Holling [22], derived two prescriptions from the study of natural systems to the management of man-made systems: First, unavoidably, important future events will be unexpected, regardless of the sophistication of up-front planning. Secondly, Holling [22] advocated substituting prediction with the capacity to absorb and accommodate unforeseen events in whatever form they may take.

Since its inception, resilience thinking has been applied in a wide range of businesses settings, including supply chains [23], business models [24] and organisations [25]. Closer to the field of PD, Crosby [26], defined project resilience as 'the ability to recover from, or adjust easily to, misfortune or change'. In this vein, Kutsch et al. [27], distinguished resilient project management from what he called 'rule-based' project management, as illustrated in Fig. 2.

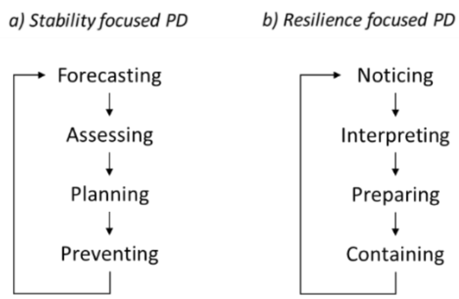

Fig. 2. Two contrasting managerial principles (adopted from [27])

Operationalising the resilience concept, Carpenter et al. [29] asked: “resilience of what to what?”, distinguishing system performance “of what” from system uncrtainties “to what?”. Applying Carpenter’s question to PD, system performance includes development time, cost and quality of the product, while uncertainties include major risks (shown in Table 2) that influence the cost, development time and quality of the product.

5. Results

This section presents the results from seven interviews, in three organizations (P1, P2 and P3), with design engineers and project managers. PM1, PM2, PM3 represents the views of project managars from P1. DE1, DE2 presents design engineer’s view from P1 and PM4 and PM5 represents the views of project managers from P2 and P3 respectively.

5.1 Risk management practices

To identify and control the risks in early phase, design engineers and project managers from all three PD organizations (P1, P2 and P3) share almost same opinion on the use of the risk management process. To identify risks, all project managers and design engineers used brainstorming technique in the early phase of the PD project, as shown in Table 1. As DE2 mentions that “we tried to sit down with key individuals in order to risk assess a new project and that would actually be done before the full project was started". All the PD organizations (P1, P2 and P3) followed the predict and plan approach to control the risks in the design phase. The project manager PM5 in P3 says that "they always try to predict problems, but I think that type of activity is quite often difficult".

The project manager PM4 in P2 mentioned that risk management practices did not get importance and management did not proritize the risk management practices. Some of the design engineers and project managers also mentioned in their statements about the failures of the predict and plan approach. The project manager PM4 in P2 states that "but the thing is every time stuff (doing risk management) takes too long, then we don't do it unless we have to". Project manager PM4 also stated that "so it's a lot of stuff that people go around, and they think about, and say, "Okay, this might be a risk," instead of writing it down. And the main risks that are being written down are in like a classic risk assessment".

The project managers in all companies categorized major risks as delay in time to market, development cost of the PD project and manufacturing cost of the product. Project manager PM5 in P3 stated that "so we would always have risk concerning time to market because we knew that we had such tight deadlines and we were pressured to work with incredible deadlines".

In one of the companies (P3) product management did not provide resources for risk mitigation planning. PM5 in P3 said that "I would often say that the risk analysis didn't get the attention and the resources it deserved, and I think one of the reasons for this is that it's very difficult".

In two companies (P1 and P3) the design engineers implemented proof of concept for high-risk design tasks as risk mitigation strategy. As stated by PM1 in P1 "all the unknowns are major risks and my approach is the proof of concept for all the unknowns". Design engineer DE2 in P1 also supported the statement given by PM1 that “if we have more prototypes then we have less risks”. All three projects faced unexpected “surprises” which were not identified during risk assessment in early phase of the PD projects.

5.2 How was resilience practiced?

The statements by the interviewees indirectly indicate that the resilience focused actions were taken by the design engineers and project managers by responding to unknown risks and suprises.

We observed that case study company P1 was having resilience focused approach in their PD project. For example the statements of DE1 and DE2 in (P1) show that the measures to handle “unexpected design issues” contribute to resilience enhanced PD process. As DE1 statets that “if something needs to be escalated, we have direct access to company owners. That’s one area which makes the company better”. He also said that “the whole reason why this company is where it is that they move so quickly has been market leader”. The company P1 was practicing “monitor and adapt” approach also to handle surprises in the design and development phase. As the PM1 in P1 says that “I do weekly meeting with my team to get feedback”. So, he was continously monitoring the risks and surprises in the design phase.

We found that PM4 in P2 mentioned little about resilience based actions to the surprises in the design phase because they were not ready to handle the surprises by not taking resilient actions. For example PM4 in P2 said that “so all of a sudden going from only having to develop one product, then all of a sudden, we need to develop six products in a very, very short amount of time”.

We found that PM5 in P3 mentioned about taking actions to enhance resilience capability by engaging experienced human resource in PD project. The PM5 said that “if we had a severe problem on a project, we had this kind of taskforce you could call it, not officially, but we knew key individuals that we could point to that problem, which would increase the likelihood of succeeding on that given problem”.

Taken together, these results suggest that risk management part was better formalized than the resilience part.

6. Analysis and Discussion

The results presented in section 5, demonstrate statements about risk management and resilience practices which influence the progress of PD projects. As aforementioned, we are using the concept proposed by Aven [10] as a theoretical lens about risk management and resilience that according to Aven [28], complement each other to manage known and unknown risks.

In case study (P1), the team members (PM1, PM2, PM3, DE1 and DE2) agree in their statements that the project was delayed due to poor risk assessment by product management in the start of the project. After one year, the product management took decision to split the project into two separate projects. As PM1 says that “but now (after one year) we find out that it is not possible. So, now we have two projects not one. This is the first example the big one splitting project into two”. Apparently, we can infer that it was due to poor “predict and plan” approach that could not identify the risk of splitting the project and planned to mitigate the risk. At the same time, the action to split the project into two is the poor example of the “resilience” approach to get back to the stable condition in the project. Because the management delayed the decision for one year and they could not continue with same PD goals. In this project, the time to market the product was identified as success criteria that is also a threshold parameter for the resilient system. As stated by DE2 that “just time is costly (in this project)”. After splitting the project into two separate projects, the project manager started “monitor and adapt” approach by using the proof of concept technique for all unknowns in the project. The proof of concept is the resilient appoach because it handles the unkown risks which is not possible by following predict and paln approach.

Now, the PM1 was using resilient focused approach by observing, responding and rebounding as shown in Fig. 2. As PM1 stated “all the unknowns are major risk and my approach is the proof of concept for all the unknowns”. The DE2 also agrees with the PM1’s statement by saying “if we have more prototypes then we have less risks”. Predict and plan approaches can be beneficial as frontloading for instance in relation to regulatory matters in PD project as PM2 stated that “so, we actually succeed involving him a lot, also in the initial planning phases. and that it's a really, really crucial part because it's where actually compliance decision can have an impact on the scope”. Yet this quote also highlights the overlap between predictive and robustness as the involvement of the person with knowledge about regulatory affairs helps to identify potential vulnerabilities in that may create unknown problems later. Risk management and planning is often perceived as connected in practice – the predictive element perceived by project personel is evident. As PM3 states that “I tend to think that awareness of risk is important, you know, if the project manager does not have any awareness about potential risks to his project, then he is getting into a corner, […] just giving some thought to what can go wrong and then try to plan accordingly”.

The project manager PM4 in P2 mentioned in his interview that risk assesment was not a priority . As PM4 said that “but the thing is every time stuff (doing risk management) takes too long, then we don't do it unless we have to”. Therefore, the “predict and plan” approach was poor in PD projects in P2 as PM4 stated, “we try to be in the project that I am now, we try to be proactive, but I think the main approach has been reactive for the many years”. The PD project faced scoped creeping which was a very big unexpected event for the design engineers as PM4 stated, “so all of a sudden going from only having to develop one product, then all of a sudden, we need to develop six products in a very, very short amount of time.” The PM4 started to use to monitor and adapt approach later in their project as PM4 stated that “we will get into how can we make sure that it’s easy to prove that this works.” using also resilient focused approach by doing the proof of concept. So, they were using mixed approaches.

The PM5 in P3 was using the brainstorming technique to identify the risks, as shown in Table 1. The product management was using the risk assessment based planning to control the identified risks in PD projects. As PM5 stated that “they always try to predict problems, but I think that type of activity is quite often difficult”. PM5 was also using resilient approach by dedicating experienced designers to solve a specific design problem and regain the normal position (as mention in section 4 about resilience). As PM5 in company P3 stated that “sometimes we would pretty much stop everything we had going and then simply create a dedicated team of software engineers and product owners to sit down and focus on solving a specific problem”.

The above discussion indicates that in case company P1, the product management was using both “predict and plan” and “monitor and adapt” appraoches. The “predict and plan” approach using risk management is focused on proactive measure to avoid risks in PD process while resilient approach address the “reality aspect” of the PD process by reducing the effects of the potential unknown risks in uncertain PD environment. The interviews in additional two companies P2 and P3 validate that risk management and resilience complement each other.

Resilience has the characteristics of agility which is to respond effectively to unexpected events and robustness which is to absorb process variations. Risk management in PDP contributes to robustness because it involves proactive planning to avoid process variation. On the other hand, risk management lacks agility because it mainly plans according to known risk with known probabilities. So, its contribution to make PDP more resilient is limited. Therefore, the PDP needs more overlaped resilience focused approach with risk management as well.

7. Conclusion

The study presented in this paper examined the hypothesis that risk management and resilience-based appraoches are complementary in PD risk management. Our case study and additional validation interviews confirmed this for the organizations that we studied.

To control known and unknown risks, the case study company (P1) used both “predict and plan” and “monitor and adapt” approaches in PD project. The product management in all three orgaizations were using dominantly either “predict and plan” or “monitor and adapt” approaches to control unknown risks and surprises in PD projects. The analysis of the empirical data shows that risk management and resilient approaches complement each other to control known and unknown risks. The analysis of the empirical data also reveals that “predict and plan” approach is an established approach while resilience based “monitor and adapt” approach is less established to handle surpises in the design process.

After studying the literature and analyzing empirical data in this paper, we suggest that by overlap of the risk management and resilience approaches the overall immunity of the PDP against known and unknown risks can be enhanced.

The present paper appears to be the first exploratory empirical study of resilience-inspired approach to PD risk management. To generalize the resilience-inspired PD risk management approach in PD projects, we propose that further empirical studies need to be conducted.

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Paper C - Planning Unplanned Design Iterations Using Risk Management and Learning Strategies

C

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Planning Unplanned Design Iterations Using Risk Management and Learning Strategies

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Abstract

Unplanned design iterations are considered one of the reasons for the high failure rate of new product development (NPD) projects. Generally, organisations employ 'proactive risk management' (PRM) and 'reactive fast learning' (RFL) to manage unplanned design iterations. This paper aims to explore how organisations employ PRM and RFL approaches to manage unplanned design iterations in the NPD process. To that end, a cross-sectional interview study was conducted in eight organisations. The interview transcripts were analysed as a primary data source using thematic qualitative text analysis technique. For PRM approach, results demonstrate that the design teams were more active in risk monitoring in the design phase as compared to risk identification in the concept development phase. Generally, design teams reduced the likelihood of unplanned design iteration risks by employing learning methods in addition to risk mitigation strategies. For RFL approach, results reveal that organisations lacked a structured approach to select suitable learning methods for fast resolution of unplanned design iterations and to convert new knowledge into organisational learning. We conclude that PRM is more established as compared to RFL in managing unplanned design iterations. We develop recommendations of how organisations can use RFL approaches more efficiently alongside PRM approaches.

Keywords: New product development process; Engineering design; Unplanned design iterations; Risk management; Organisational learning

1. Introduction

The successful design and development of new products is an essential business endeavour in today's competitive business environment. To design, develop and launch new products in the market, companies use various procedures and methods categorised under new product development (NPD) (Ulrich and Eppinger 2016). In NPD processes, the aim is to minimise the development cost and time-to-market while improving the quality of products (Olechowski et al. 2012, Oehmen et al. 2010). However, the rate of NPD projects failing to meet the goals in terms of development cost and time, and reach the market is high. Barczak, Griffin, and Kahn (2009), for example, observed that approximately 40% of NPD projects fail to enter the market. One reason why NPD projects encounter failure is due to the undesirable design iterations in the NPD process (Ballard 2000). As Ballard (2000) stated that informal surveys of design teams have revealed that design teams spent up to 50% of design time on needless or undesirable design iterations.

Design iterations comprise work containing correction, interdependency, or feedback (Unger and Eppinger 2002). However, explicitly, unplanned design iterations often arise in the form of rework when mistakes or feedback loops, unexpectedly, require a step backwards in the design phase (Unger and Eppinger 2009). By the very nature of NPD, design iterations are unavoidable and, in many cases, essential to create value in the design process (Krehmer, Meerkamm, and Wartzack 2009). However, the unplanned design iterations often cause delays and cost overrun in NPD projects as documented in the literature (Mujumdar and Maheswari 2018, Eppinger, Nukala, and Whitney 1997, Krishnan, Eppinger, and Whitney 1997, Smith and Eppinger 1997, Smith and Tjandra 1998, Sobek II, Ward, and Liker 1999, Costa and Sobek 2003, Jin and Chusilp 2006).

The existing body of research on 'design iterations' in NPD process generally has been restricted to the early detection of the potential design iterations, to avoid or plan the design iterations (Meier, Yassine, and Browning 2007). For example, to prevent or plan the design iterations, some studies refer to forecasts of design iterations using design structure matrices, modelling of the design process, buffering the design phase (Wynn, Eckert, and Clarkson 2007), selecting suitable product development methods and using genetic algorithms (Meier, Yassine, and Browning 2007). These techniques address identification and sequencing 'planned design iterations' to optimise planning in NPD process. However, we contend that these techniques are poorly suited to managing unplanned design iterations because of their focus on predictable - and thus 'plannable' - design iterations only.

In an increasingly complex and uncertain product development context, unplanned design iterations are generally unavoidable (León, Farris, and Letens 2012) and have become a significant source of change risk propagation in the NPD process (Li et al. 2020). Therefore, instead of solely aiming to avoid unplanned design iterations, the aim should also be to manage unplanned design iterations in the NPD process and maximise the value each iteration generates for the overall design process (León, Farris, and Letens 2012). Hence, this paper focuses on making a contribution to managing unplanned design iterations in the NPD process.

Generally, design teams cannot predict which unplanned design iteration will occur when in the NPD process. However, to manage unplanned design iterations, design teams can probe potential triggers that cause unplanned design iterations. Triggers of unplanned design iterations include unclear requirements at the beginning of the NPD process, design complexity, technology uncertainty, errors or unforeseen design changes and update of new information (Eppinger 2001, Krehmer, Meerkamm, and Wartzack 2009, Mujumdar and Maheswari 2018). As unplanned design iterations are, by their nature, based on the occurrence of unplanned rework, we conceptualise an unplanned iteration for the purpose of this paper as the occurrence of a specific class of product development project risk. With risk being defined as the impact of uncertainty on objectives (ISO 31000, 2018), unplanned design iterations are therefore considered a class of uncertain events that negatively impact an NPD project schedule.

These risks can fall into two categories: Foreseen risks, i.e., foreseen possible, unplanned iterations identified as a risk during risk assessment, but deemed not severe enough to warrant proactive mitigation actions during the planning process. And unforeseen risk, i.e., unforeseen iterations that were not identified during the risk management or other planning processes (Aven and Kristensen 2019).

Generally, two different approaches are practised to manage foreseen and unforeseen risk events that cause unplanned design iterations in the NPD process, 'proactive risk management' (PRM) and 'reactive fast learning' (RFL). The first approach is a 'proactive risk management' (PRM) approach, which identifies and assesses the (now foreseen) risks, at the start of the NPD projects, and subsequently implements a risk mitigation strategy to reduce the risk (either their likelihood of occurrence or significance of their impact) of unplanned design iterations (Unger and Eppinger 2011, Unger and Eppinger 2002). For example, at the beginning of NPD process, a PRM approach would identify the risks surrounding the clarity of design requirements and plan strategies for continuous and up-front requirements elicitation and validation to reduce the risk of costly unplanned design iterations in later stages of NPD process. However, literature studies reveal that a large proportion of design risks affect the performance of NPD process either before their identification, or after they were identified but not managed appropriately (Thamhain 2013, Beauregard 2015). In conclusion, the PRM approach reduces the number of unplanned design iterations by better identifying and subsequently proactively mitigating foreseen risks. There remains a significant potential to both better identify those risks, as well as developing improved mitigation actions to reduce the occurrence and impact of unplanned design iterations.

The second approach is 'reactive fast learning' (RFL), which primarily reduces the adverse impact of unplanned design iterations by building general organisational capabilities to deal with their occurrence more effectively. The RFL approach employs learning strategies to resolve unplanned design iterations faster, as well as generating greater progress from the iteration (and thus reducing the probability of subsequent iterations). The RFL approach uses learning strategies to increase technical and process related knowledge, which ultimately leads to faster resolution of unplanned design iterations. For example, an unforeseen introduction of new technology in a sub-system can cause an unplanned design iteration. It can be managed, as it emerges, by accelerated learning through fast testing of the technology and tools. In conclusion, the RFL approach reduces the adverse impact of unplanned design iterations by faster resolution using learning strategies.

An NPD process cannot completely prevent all unplanned design iterations. However, one possibility is to manage unplanned design iterations by reducing the 'number' of design iterations or reducing the 'impact' of unplanned design iterations on the progress of the NPD projects. We hypothesise that the combined utilisation of PRM and RFL approaches can better perform (than the present situation mentioned in the literature) in managing unplanned design iterations. The effective utilisation of both approaches can only be possible if design teams understand how and when these approaches are suitable to employ in their specific real-world scenarios. However, to our knowledge, there have been no empirical studies investigating when or how organisations use the PRM and RFL approaches, what types of foreseen and unforeseen risk events (which cause unplanned design iterations) are managed by each (or both) approaches, what kind of risk mitigation and learning strategies are used and how both approaches overall perform to manage undesirable unplanned design iterations in NPD process. The main aim of this paper, therefore, is to explore the utilisation of PRM and RFL, in a real-world scenario, by product development organisations in managing unplanned design iterations. To explore the practices of PRM and RFL approaches in the product development organisations, we ask the following research question: How do organisations employ both 'proactive risk management' approach, as well as 'reactive fast learning' approach, to manage unplanned design iterations in the NPD process?

We aim to understand in which circumstances the two approaches, either separately or combined, are used and how they identify and mitigate the risk of unplanned design iterations. More specifically, the contributions of this paper are: (a) literature-based study of existing NPD and engineering management literature and their mapping on PRM and RFL approaches (Section 3); (b) description and classification of triggers of unplanned design iteration risks observed in the empirical study (Section 4); (c) description of performance aspects of contemporary methods used in PRM and RFL approaches based on empirical observations of industrial practice (Section 5). This paper contributes, in broader terms, to the stream of work on the design research (Cash 2020) and more specifically of design methods and tools (Unger and Eppinger 2002, Unger and Eppinger 2011, Morkos, Shankar, and Summers 2012, Hsiao et al. 2016, Glover and Daniels 2017).

The remainder of the paper is organised as follows: Section 2 describes the research methodology used to collect and analyse empirical data from industrial practice. Section 3 lays out the literature-based results of the research, describing PRM and RFL approaches in the NPD process. Section 4 presents the results of the empirical study conducted in companies that demonstrate the description and classification of unplanned design iteration risks; practical use of PRM and RFL approaches in the NPD process. Section 5 discusses the implications of the results of the study. Section 6 finally concludes the discussion and suggests future work for the better utilisation of the PRM and RFL approaches in the NPD process.

2. Method

2.1 Research Design

The empirical elements of our paper follow a deductive research approach (Bell, Bryman, and Harley 2018) as we attempted to empirically understand how organisations practice PRM and RFL to manage unplanned design iterations. The most suitable research method for the present work is employing the cross-sectional study (Bell, Bryman, and Harley 2018) as the nature of the study is exploratory. In the cross-sectional study approach, we selected semi-structured interviews as a primary data source to gain a detailed understanding of PRM and RFL used in NPD process. In semi-structured interviews, we endeavoured to achieve reliability and consistency by using an interview script that established the topics to be addressed (Shafqat et al. 2019b) during interviews.

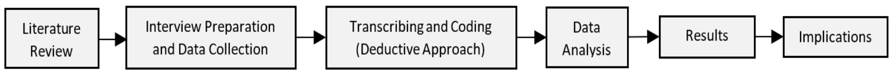

Figure 1. Outline of the research method

Figure 1 illustrates a complete view of the research work divided into 6 phases. In the first phase, to answer the research question and facilitate the empirical study, we reviewed existing NPD and engineering management literature and mapped it on the two approaches, PRM and RLF. For the overview of the literature, we used Scopus and Science Direct databases. In searches, we focused on the titles, keywords and abstracts of the peer-reviewed papers. The following research strings were used with Boolean operators: ("product development process" AND "design iterations"), (new AND "product development" AND process OR projects AND "design iterations" OR "unplanned design iterations"), ("new product development" OR "product development" AND "risk management"), ("new product development" OR "product development" AND "risk management" AND "design iterations" OR "unplanned design iterations"), (New AND "product development" AND method AND risk AND management), ("new product development" OR "product development" AND learning AND "design iterations") and ("innovation" AND "learning"). After the initial screening of the titles of the papers, the abstract, the introduction and the conclusion sections, we found 37 relevant research articles for the closer overview. We studied all chosen articles in detail and mapped the (21) most relevant literature in Section 3.

In the second phase, by using literature review, we prepared the interview questionnaire and conducted interviews to collect data. We conducted fourteen semi-structured interviews in eight companies which were involved in NPD projects (explained in section 2.2). In the third phase, we transcribed, read and got familiar with the data, which helped us to identify how and when PRM and RFL approaches were used in industrial practices. Then, we coded interview data using a deductive approach with the help of ATLAS.TI software (explained in Subection 'Data Analysis'). In the fifth phase, we complied results under emerging themes (PRM and RFL) from the deductive approach. Finally, we discussed the results and implications for managing unplanned design iterations in NPD process. The next two sub-sections (Data Collection and Data Analysis) describe the details of the 'Interview preparations and data collection', 'Transcribing and coding' and 'Data analysis' phases of the present research work.

2.2 Data Collection

We conducted fourteen interviews with CEOs, R&D directors, project managers and design engineers in eight selected companies which were all deeply involved in NPD projects. Table 1 presents an overview of the interviewee's job responsibility in each of the companies. We mainly conducted face-to-face interviews (11 participants) and held the remaining interviews (3 participants) over the phone. The interviews were conducted in eight Danish companies. The case companies were selected based on a set of criteria, including (1) companies with in-house product development, (2) physical products, (3) companies with ongoing NPD projects, and (4) headquartered in Denmark. We tried to avoid bias caused by cultural anomalies by focusing on the case companies in a single national context, i.e., Danish companies with in-house NPD projects. To ask for participation in the study, we contacted the interviewees via email, clearly explaining the purpose of the research.

During the course of the interviews, the interview script combined open and closed questions aiming to explore three topics 1) how PRM was performed in the NPD process 2) when and how PRM failed to mitigate (foreseen and unforeseen) risks of unplanned design iterations 3) how RFL approach helped or failed to reduce the impact of unplanned design iterations due to foreseen and unforeseen risks in NPD process. We used 'snowballing' (Bell, Bryman, and Harley 2018) as the sampling strategy during the interviews due to the exploratory nature of the study. We asked participants to provide as much detail as possible regarding their experience about managing unplanned design iterations using PRM and RFL approaches. We asked "what if" questions to find out the participant's perceptions about managing unplanned design iterations by using risk management and learning methods. We recorded the interviews, lasting 45 and 60 minutes, on a digital audio recorder and transcribed using professional transcription service.

Table 1. Case company background, number of interviews and interviewee details.

Company ID	Industry	Major Business Region	Number of interviews at the company	Interviewee Job Area
Company A	Health Care	Global	5	A1: DE A2: DE A3: PM A4: PM A5: PM
Company B	Health Care	Global	1	B1: PM
Company C	Mining	Global	1	C1: PM
Company D	Health Care	Global	3	D1: DR&D D2: LE D3: RMg
Company E	Health Care	Global	1	E1: CEO
Company F	Oil & Gas	Nordic	1	F1: CEO
Company G	Oil & Gas	Global	1	G1: BRD
Company H	ICT	Global	1	H1: PM

Note: DE = Design engineer, PM = Project manager, DR = Director R&D, RMg = Risk manager, LE = Lead engineer, CEO = Chief executive officer, BRD = Business Risk Director

2.3 Data Analysis

To examine the practices of using PRM and RFL approaches in managing unplanned design iterations and various types of foreseen and unforeseen risks, we used thematic qualitative text analysis technique (Kuckartz 2014). We analysed interview transcriptions as a primary data source. To address our research question, we coded each transcript multiple times and identified the relevant segments using ATLAS.TI software.

In the first step, to examine the participant's perceptions in the light of risk management and learning theories, we initiated data analysis primarily with a deductive research approach (Bell, Bryman, and Harley 2018). We developed literature review-based thematic categories (Kuckartz 2014), and coded interview transcripts using thematic categories as used by Field and Chan (2018). The codes included words, phrases or complete answers to the questions asked during the interviews (Saldaña 2015). For example, the thematic category 'risk assessment in NPD process' from the thematic area 'reducing unplanned design iterations using PRM' consists of all codes, including actions and tools, used to identify risks in the NPD process. We coded all the instances, which were providing relevant information; for example, events related to risk management (PRM) activities and learning activities (RFL) employed to manage unplanned design iterations (presented in Section 4).

In the next step, we analysed the codes from the previous step, with a theoretical lens from Section 3 (PRM and RFL – Literature Perspective), by inquiring whether the identified codes help us answer the research question. In the last phase, we categorised all the final codes under the thematic areas of *'reducing the unplanned design iterations using PRM'* and *'reducing the impact of unplanned design iterations using RFL'* in the NPD process. To answer the research question, the results from data analysis provided the basis to discuss (in "Discussion" Section) both (PRM and RFL) approaches in the NPD context.

3. Proactive Risk Management (PRM) and Reactive Fast Learning (RFL) – Literature Perspective

3.1 Proactive Risk Management Approach in NPD Processes

3.1.1 Fundamentals of Risk Management in NPD

Risk management is an essential part of NPD (Oehmen et al. 2010). Design teams commonly employ a risk management strategy to identify and manage risks in the NPD process. The well-accepted definition of risk covers positive (opportunity) and negative (threat) aspects of risk. The project management body of knowledge defines risk as 'an uncertain event or condition that, if it occurs, has a positive or negative impact on project objectives' (PMI, 2008). However, in this paper, we discuss only identifying and managing negative aspect of risks that can cause undesirable, unplanned design iterations in NPD process. Therefore, we adopt the definition of risk from the ISO 31000 (2018) standard as risk being the effect of uncertainty on the NPD process's ability to meet its objectives. Uncertainties about critical events that may affect the performance of NPD projects are the causes of risks (Oehmen and Seering 2011). In a literature review, Oehmen et al. (2020) presented three fundamental sources of uncertainties which cause risks in NPD projects such as technology (e.g., risks arising from technology maturity), market (e.g., risks arising from changing customer expectations) and management (e.g., risks arising from organisation and processes).

In the context of the present paper, we define risk management as 'the process to uncover and manage risks in the NPD process, following a structured approach by initiating timely mitigation actions to avoid, transfer or reduce risk likelihood or impact' (AS/NZS, 1999). According to the ISO 31000 (2018) standard, the core elements of the risk management process are as follows: establishing the context, risk assessment (including risk identification, risk analysis, and risk evaluation), risk treatment, monitoring and review, and communication and review.

3.1.2 Proactive Risk Management (PRM) and Unplanned Design Iterations

Generally, NPD processes emphasise increasing the efficiency of the product design system. To minimise the number of unplanned design iterations, NPD process (usually) do not focus on reduction of uncertainty, even though it has the capability to reduce the uncertainty in a structured way (Oehmen and Seering 2011). Risk assessment, which is an integral part of the risk management process, plays a proactive role to identify, analyse and evaluate the risks that cause unplanned design iterations in the NPD process. Consequently, risk assessment in the NPD process enables companies to predict the potential risks and plan suitable actions for risk treatment (IEC 31010, 2009). Therefore, considering proactive approaches to manage risks that cause unplanned design iterations, traditional risk management can be associated with PRM approach in the NPD process. Employing a PRM approach to predict and evaluate the risks in the NPD process, design teams use different tools and techniques. The tools and techniques, which are typically used in risk assessment according to ISO/IEC standard (IEC 31010 2009), include, e.g., risk identification checklists, brainstorming, primary hazard analysis, hazard and operability studies, failure mode effect analysis, risk indices, bow tie analysis, fault tree analysis, cause and effect analysis, root-cause analysis, event tree analysis, fishbone tool, etc.

We hypothesise that a PRM approach is suitable for NPD projects having low uncertainty and less complexity, e.g., incremental innovation type projects. High uncertainty and complexity in the NPD projects are accompanied by lack of (structured) process and technical knowledge that are necessary to employ PRM methods successfully (Aven and Kristensen 2019) as mentioned above, radical innovation type projects. Therefore, to reduce the number of design iterations, NPD projects with low uncertainty levels can identify a significant number of risks and plan mitigation actions accordingly (Unger and Eppinger 2009). For example, NPD projects with incremental innovation have low process and technical uncertainty levels, as most of the tasks are known through 'similar' previous projects. Therefore, arguably, the design team is fundamentally in a position where it can identify relevant risks using process, experience and technical knowledge.

At the same time, the PRM approach becomes increasingly problematic in a highly uncertain project environment, as it becomes increasingly difficult to identify and control risks early enough in the project reliably; i.e., before a risk manifests in an unplanned design iteration. Naturally, radical innovation type NPD projects have a high degree of process and technical uncertainty, as for example, full requirements are not known a priori and novel technical knowledge may be required to develop the product. Consequently, it is most likely that significant risks may not be identified by design teams using PRM at the start of the NPD process. For instance, Thamhain (2013), argues that risk assessment phase generally fails to predict the majority of the risks in NPD process, and the unidentified risks affect the performance of the NPD process in later stages.

3.2 Reactive Fast Learning Approach in the NPD Processes

3.2.1 Fundamentals of Learning in NPD

Learning activities enhance the capability of the design teams to address design challenges occurring in the design phase of NPD process (Shafqat et al. 2019a). Persidis and Duffy (1991) state that "designers learn when they encounter knowledge which is sufficiently different from their present state of knowledge". Persidis and Duffy (1991) describe that the learning consists of three sub-processes, including acquisition, generation and modification. They further explain that the acquisition represents the process to receive new knowledge or information; the generation presents creating new from the general knowledge, and the modification describes the process of altering the general knowledge. In the context our study, we consider that learning occurs when the design teams face design challenges and acquire new knowledge along with the process related knowledge and technical knowledge; generate solutions to resolve unplanned design iterations by modifying the existing knowledge; and increase the process knowledge and technical knowledge at the individual, team and organisational levels.

There exist several studies, which examine learning in connection with product development projects (Persidis and Duffy 1991, Cooper, Kenneth G. 1993, Lynn, Morone, and Paulson 1996, Lynn, Akgün, and Keskin 2003, Akgün, Lynn, and Yılmaz 2006, Cui, Chan, and Calantone 2014, Erichsen et al. 2016, Un and Rodríguez 2018). To further understand learning in the RFL approach, we consider single-loop and double-loop learning theories by Argyris and Schön (1997). Argyris and Schön (1997) define single-loop learning as a process of error detection and correction, which permits the organisation to follow its current policies. To describe learning associated with the RFL approach in the context of single-loop learning, we take the example of addressing unplanned design iterations in the later stages of NPD process. To resolve unplanned design iterations, the design team acquires new knowledge and develop new (technical) solutions on the product level. In this process, the requirements of the NPD project remain the same, and the NPD project execution processes also remain unchanged. The design team successfully resolves the unplanned design iterations, which can be associated with single-loop learning.

Argyris and Schön (1997) define double-loop learning as a process which modifies the organisation's underlying policies and objectives in the error detection and correction process. To describe the RFL approach in the context of double-loop learning, we take the example of the improvements in the organisation's standard operating procedures related to NPD project management or problem-solving process as a result of new knowledge gained in resolving the unplanned design iterations (including improvements to the risk management process). Therefore, the new solutions to the problems not only improve the product itself but also contributes to the overall knowledge of the organisation, which can be used to other projects. For example, Technical Review Boards, such as those used after the explosion of a Concorde jet in

2000, illustrate double-loop learning at the level of an entire industry (Cusick, Cortes, and Rodrigues 2017).

3.2.2 Reactive Fast Learning (RFL) and Unplanned Design Iterations

To deal with unplanned design iterations in the NPD process, in the RFL approach individuals, design teams and organisations learn about new solutions of unplanned design iterations. As mentioned above, in learning loops, design teams enhance process related knowledge and technical knowledge by using different methods for knowledge acquisition, generation and modification, collectively labelled as 'learning methods'. In a literature review, Shafqat et al. (2019a) summarised learning methods used in the design phase to solve design problems in the perspective of RFL. They categorised the learning methods into formal and informal learning methods (Shafqat et al. 2019a, Dalmaz, Possamai, and Armstrong 2015). The formal learning methods include past product reviews (Lynn, Akgün, and Keskin 2003); outsourcing (Un and Rodríguez 2018); prototyping and experiments (Erichsen et al. 2016); knowledge acquisition (Henshall, Campean, and Rutter 2017); and learning by doing (Cui, Chan, and Calantone 2014, Henshall, Campean, and Rutter 2017). The informal learning methods include learning from incidents (Drupsteen and Guldenmund 2014, Henshall, Campean, and Rutter 2017); product failure (Henshall, Campean, and Rutter 2017, Drupsteen and Guldenmund 2014); and learning from teammates and mentors (Leifer and Steinert 2011).

In the RFL approach, to resolve the unplanned design iterations, the design team employs suitable learning methods and quickly learn about solutions. However, learning methods are not necessarily efficient solutions in terms of time and money (Shafqat et al. 2019a). They can be prohibitively expensive and reduce the efficiency of the NPD process by increasing the development cost and time to market. Therefore, arguably, RFL methods should only be employed if a) PRM-based approach is inapplicable due to the level of uncertainty and complexity faced by the NPD project (Tegeltija et al. 2016) and b) the organisation has developed generic capabilities to execute RLF methods quickly and on short notice while maximising the amount of knowledge the generated (Shafqat et al. 2019a).

In the next sections, we analyse the interview data regarding practices of risk management and learning methods; and overall performance of the PRM and RFL approaches in managing unplanned design iterations.

4. Results of Interview Study

This section presents the results of an empirical study on the interviewee's perceptions of managing unplanned design iterations using PRM and RFL approaches. We divide it into two subsections which describe the results based on the thematic areas as described in the method section, including the thematic areas *'reducing unplanned design iterations using PRM'* and *'reducing the impact of unplanned design iterations using RFL'*.

4.1 Reducing Unplanned Design Iterations using Proactive Risk Management

In this section, we introduced an overview of how and when design teams employ risk management to identify and mitigate (foreseen) unplanned design iteration risks using the following 4 thematic categories (as shown in figure 2): *risk assessment in NPD process; risk mitigation strategies in NPD process; risk monitoring in NPD process; triggers of unplanned design iterations in NPD process.*

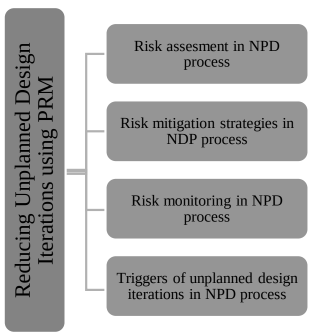

Figure 2. Thematic categories from thematic area 'reducing unplanned design iterations using PRM

4.1.1 Thematic Category 1.1: Risk Assessment in NPD Process

Generally, almost all organisations employed a traditional risk identification process at the start of the projects for fulfilling the requirement to proceed to the next phases of the NPD process. We observed in the data analysis that some health care companies made risk assessment mandatory from concept selection until the product was in the market. For example, the CEO of health care company (E) stated that *'projects are required to perform risk analysis from their concept selection until the device is in the market'* (E1-E). On the other hand, an IT company (H) did not use risk assessment in a structured way to identify the risks. This may be exemplified by a project manager from the IT company who stated that *'we are not using risk management explicitly'* (H1-H).

To identify risks of unplanned design iterations in NPD projects, the engineering design teams utilised risk management experts from the same health care organisation (D). A lead engineer stated that *'I don't do risk analysis as such, but I assess together with our risk manager'* (D2-D). In some cases, the companies outsourced the risk assessment process; a project manager (C1) stated that *'in some cases, it (risk assessment) is outsourced'* (C1-C). However, in the risk assessment process, the engineering design teams also expressed lack of confidence in external risk management experts. For example, a lead engineer (D2) expressed his concerns as *'(during) the risk assessment of the different functions (of product), if I don't sort of agreeing to them (external risk assessment) or believe in them […]. So, I start challenging those requirements, and the risk analysis, and then we have a dialogue (with external risk managers)'* (D2- D).

We observed that design teams most frequently employed HAZOP, FMEA and brainstorming for identifying and assessing the risks at the front-end of the NPD process. The companies did not use advanced computational methods to predict unplanned design iteration risks, for example, using 'Monte Carlo' simulations. A risk manager (D3) from health care company (D) stated that *'for project risks we use PowerPoint and Word […] and from the first concept, the first design, we will do* *iterations on HAZOP, and on FMEA'* (D3-D). In some cases, however, the design teams did not get enough resources to perform risk analysis. A project manager (A5) stated that *'I would often say that the risk analysis didn't get the attention and the resources, and I think one of the reasons for this is that it's challenging.'* (A5-A).

The data analysis revealed that almost all identified foreseen risks belonged to technology and schedule-related risks. For example, a lead engineer (D2) form health care company (D) stated that *'I would say that we have struggled with […] the technical design risks […] with regards to usability, ensuring that it's easy for patients to use'* (D2-D). Regarding schedule-related risks, a design engineer (A2) from another healthcare company (A) stated that *'we would always have risk concerning time to market'* (A2-A).

4.1.2 Thematic Category 1.2: Risk Mitigation Strategies in NPD Process

Overall, we observed that along with employing various risk mitigation strategies, the engineering design teams also tried to reduce unplanned design iteration risks by deliberately planning design iterations in the design phase of the NPD process. In the planned design iterations, the design teams were mostly using prototyping, simulations and testing for mitigating technical risks. For example, a lead engineer (D2) from a health care company (D) stated that *'(after risk assessment) then it's my role to figure out, well, what's the most effective way forward. So, I can say do either simulation or some experimentation or this kind of things to mitigate the technical (unplanned design iteration) risks'* (D2-D). Another design engineer (A1) confirmed this by stating *'If we have more prototypes, then we have fewer risks'* (A1-A).

In case of technical risks, failing fast was another option of the companies to choose alternative risk mitigation strategies. For example, a project manager (C1) stated that *'we do have some cases where it (engineering design) failed technologically […] that's an inherent part of the project, to get to that failure point as early as possible. And if you get to it, then you start over'* (C1-C).

We observed in one NPD project that the design teams experienced re-occurring risks despite using risk mitigation strategies. For example, a project manager (C1) mentioned that *'we have a couple of risks that keep re-occurring […] and we are trying to mitigate them, but they are still re-occurring because they are hard to mitigate'* (C1-C).

4.1.3 Thematic Category 1.3: Risk Monitoring in NPD Process

To monitor unplanned design iteration risks in the design phase, almost all interviewees stated that continuous risk monitoring was an effective method. The design teams were more vigilant in risk identification in the design and development phase than in the conceptual phase or planning phase of the NPD process. For example, lead engineer D2 in health care company (D) stated that *'I use very active risk assessment (in the design phase) and I think it's become apparent also to others that it's a pretty effective way of working'* (D2-D).

In almost all organisations, usually, project managers held weekly or biweekly informal meetings with design teams to update the list of technical risks. In these meetings, the design teams did not invite risk management experts to identify risks. For example, lead engineer (D2) stated that *'I do it (risk assessment) continuously, but once a week we have a tech meeting which I run, and the sort of the core in that meeting is our technical risk grid. So whatever challenges we have […] I put them all into this risk grid if it's not OK, and we use that for prioritisation'* (D2-D). However, we also observed in a few NPD projects that there was lack of communication and ownership in design teams to monitor and report the risks to higher management. For example, a business risk director from company (G) stated that *'we try to have these meetings regularly and you create risk reports and so on. And basically, I have found it very, very difficult to make that work'* (G1-G).

Some of the design engineers reported it is hard to perform risk monitoring, and their approach is more reactive than proactive. A project manager (A5) from company (A) expresses his opinion as *'in the project that I am now, we try to be proactive (in risk monitoring), but I think the main approach has been reactive for the many years'* (A5-A).

4.1.4 Thematic Category 1.4: Triggers of Unplanned Design Iterations in NPD

We observed that the design teams did not consider several triggers of unplanned design iterations during the risk assessment and risk mitigation phases. During the interview study, several respondents mentioned triggers of unplanned design iterations including tight project schedule, changing product requirements, lack of communication between design teams, the bias of the people, lack of knowledge and experience in designing the product and complexity of the product under development.

For example, lead engineer (D2) stated that 'our biggest challenge is that the requirements are not well-defined from the customer side (D2-D). Project manager (A4) confirmed this as he stated that *'I think some of the main problems are not being able to define the requirements in the early stages and continuously evolving requirements'* (A4-A). When asked about triggers of unplanned design iterations, a project manager responded: *'I think from this project, it's primary communication if we don't communicate efficiently, […] then we often do double work'* (D2-D). We observed that in the development of medical devices, predominantly squeezed timelines was the main trigger of unplanned design iterations.

We observed in some of the NPD projects, additional triggers of unplanned design iterations including human error, willingness to take the risk, lack of ability to assess user needs, lack of continuous risk assessment in the later stages of the NPD process. For example, a project manager mentioned taking risk on purpose as a potential trigger to the unplanned design iterations. The project manager stated that *'we would say that we have a high risk of hitting this problem. We need this (action) to prevent it, and then they (higher management) were often willing to take that risk […] then we* *would hit it, and then the project would be delayed'* (A5-A). Another project manager (C1) expressed his concerns about the lack of ability to assess user needs. The project manager mentioned that *'for our part of development, our biggest challenge is getting a customer on board with testing (the equipment for assessing the user needs)*' (C1-C).

In summary, the perceptions of reducing unplanned design iterations using PRM approach varied. We illustrated the content considered important in the current section ('Reducing Unplanned Design Iterations using PRM') and Table 2.

Table 2. Summary of important results from 4 thematic categories.

Thematic category (Subsection)	Empirical Results	Illustrative quotes	
Thematic Category 1: Risk assessment in NPD process	Generally, design teams employed risk assessment process with the help of risk management experts, and some design teams did not use risk management	*'I don't do risk analysis as such, but I assess together with our risk manager' (D2-D)*	*'we are not using risk management explicitly' (H1-H)*
	Design teams most frequently applied HAZOP, FMEA and brainstorming for identifying and assessing the risks. Some design teams did not get enough resources to perform risk analysis	*'for project risks we use PowerPoint and Word […] and from the first concept, the first design, we will do iterations on HAZOP, and on FMEA' (D3-D)*	*'I would often say that the risk analysis didn't get the attention and the resources, and I think one of the reasons for this is that it's challenging.' (A5-A)*
Thematic Category 2: Risk mitigation strategies in NPD process	The design teams mostly used learning methods, e.g. prototyping, simulations and testing for mitigating technical risks	*(after risk assessment) then it's my role to figure out, well, what's the most effective way forward. So, I can say do either simulation or some experimentation or this kind of things to mitigate the technical (unplanned design iteration) risks'* (D2-D)	*'If we have more prototypes, then we have fewer risks'* (A1-A)
	In case of technical risks, failing fast was another option of the companies to choose alternative risk mitigation strategies. It was also observed in some NPD projects that the design teams experienced re-occurring risks despite using risk mitigation strategies	*'we do have some cases where it (engineering design) failed technologically […] that's an inherent part of the project, to get to that failure point as early as possible. And if you get to it, then you start over'* (C1-C)	*'we have a couple of risks that keep re-occurring […] and we are trying to mitigate them, but they are still re-occurring because they are hard to mitigate' (C1-C)*
Thematic Category 3: Risk monitoring in NPD process	Almost all design teams stated that continuous risk monitoring was an effective method and some design teams showed lack of communication and ownership to monitor and report risks to higher management	*'I use very active risk assessment (in the design phase) and I think it's become apparent also to others that it's a pretty effective way of working'* (D2-D)	*we try to have these (risk monitoring) meetings regularly and you create risk reports and so on. And basically, I have found it very, very difficult to make that work'* (G1-G)
Thematic Category 4: Triggers of unplanned design iterations	Several respondents reported triggers of unplanned design iterations including tight project schedule, changing product requirements, lack of communication between design teams, the bias of the people, lack of knowledge and experience in designing the product and complexity of the product under development	*'I think some of the main problems are not being able to define the requirements in the early stages and continuously evolving requirements'* (A4-A)	*'I think from this project, it's primary communication if we don't communicate efficiently, […] then we often do double work'* (D2-D)
	Some respondents also reported additional triggers of unplanned design iterations including human error, willingness to take the risk, lack of ability to assess user needs, lack of continuous risk assessment in the later stages of the NPD process	*'we would say that we have a high risk of hitting this problem. We need this (action) to prevent it, and then they (higher management) were often willing to take that risk […] then we would hit it, and then the project would be delayed'* (A5-A)	*'for our part of development, our biggest challenge is getting a customer on board with testing (the equipment for assessment of the user needs)'* (C1-C)

4.2 Reducing the Impact of Unplanned Design Iterations using Reactive Fast Learning

In this section, we present a summary of results on how and when design teams employ learning strategies to reduce the impact of unplanned design iterations. It is divided into the following 3 thematic categories (as shown in figure 3): *most frequent learning methods to resolve unplanned design iterations; learning from mistakes and failures in NPD process; most re-occurring unplanned design iterations in NPD process*. Together, these results provide insights into various aspects of using the 'RFL' approach, including the selection of learning methods, utilisation of learning methods and organisational learning.

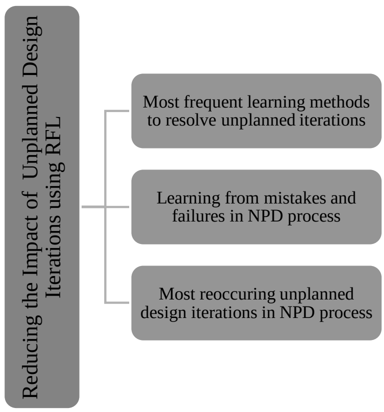

Figure 3. Thematic categories from thematic area 'reducing the impact of unplanned design iterations using RFL'

4.2.1 Thematic Category 2.1: Most Frequent Learning Methods to Resolve Unplanned Design Iterations

To resolve unplanned design iterations, the interviews mentioned that the design teams employed various learning methods to acquire information and processing it to new knowledge. For example, the interviewees frequently referred to the use of prototyping, experimentation, testing, proof of concept, outsourcing and assistance from technical experts. However, in general, the companies lacked a proper selection criterion for the most suitable learning methods to resolve unplanned design iterations. A lead engineer stated that *'if we have three possible solutions to a problem, then we often just have to select one of them that we believe in, and sometimes pick the wrong choice'* (D2-D).

We observed that prototyping was a commonly employed learning method to resolve unplanned design iterations. For instance, company (C), which was designing and manufacturing mining equipment, used prototyping in all phases of the NPD process. Another interviewee, when asked about prototyping said: *'we have several SLA (stereolithographic apparatus) machinery for building prototypes in very high quality. So, this is something that we have a high focus on it'* (C1-C). In addition to prototyping, design teams also applied testing and experimentation to resolve unplanned design iterations. For instance, a lead engineer (D2) stated that *'sometimes testing can be very cumbersome and even if we do calculations, they always contain assumptions. Sometimes we see that some of these assumptions don't hold true and then we just have to learn that we underestimated that one (assumption)'* (D2-D).

4.2.2 Thematic Category 2.2: Learning from Mistakes and Failures in NPD Process

Learning from failures and mistakes is the informal learning method to reduce unplanned design iterations in the next phases of the NPD process and future projects. The data analysis indicates that most of the companies lacked a structured process for converting knowledge from failures and mistakes into organisational learning. For example, a project manager (C1) stated that *'we have tried (to establish a process), but we don't have a consistent process for our lessons-learned, and it is something that is on the table. There is a framework to do that, but that framework is currently not running'* (C1-C).

On the other hand, the health care company (D) used a special task force to secure the new knowledge and transfer it to other projects. As the R&D manager (D1) stated that *'we have tried to make databases on this (to secure knowledge), and it ends up in not* *being used. People are so busy with the projects, so they don't use all this stuff. What we instead do is that we try to circulate people between projects, bringing knowledge from one project to another'* (D1-D).

4.2.3 Thematic Category 2.3: Most Frequent Unplanned Design Iterations

Mostly, the focus of engineering design teams was on forecasting and mitigating the risks of unplanned design iterations. Generally, during the NPD projects, the engineering design teams could not reduce the unplanned design iterations regarding changing requirements and complexity of the product. A project manager (B1) stated that *'I think some of the main reasons of the problems (unplanned design iterations) is that I am not able to define the requirements in the early stages (of NPD process). The requirements keep evolving the further you get in the process'* (B1-B). Regarding product complexity, R&D director (D1) of health care company (D) mentioned that *'we are facing challenges (unplanned design iterations), especially for those parts that are combination (complex) products. The products where you have the medicine integrated into the device'* (D1- D).

The unplanned design iterations impacted the timeline and development cost of the NPD projects. We noticed that the cost overrun was not the critical impact of the unplanned design iterations in the health care companies. A risk manager (D3) from health care company (D) stated, *'I would say normally, the delay would be more important than the cost overrun'* (D3-D). A project manager (A4) from another healthcare company stated: *'when we didn't manage to resolve (unplanned design iterations), […], everything delayed on the project, and often also delays in time to market'* (A4-A).

In summary, the respondents expressed their various views about using learning methods to reduce 'the impact' of unplanned design iterations. We have presented important results in this section ('Reducing the impact of unplanned design iterations using RFL') and Table 3.

Table 3. Summary of important results from 3 thematic categories with thematic area 'reducing the impact of unplanned design iterations using RFL'.

Thematic category (Subsection)	Empirical Results	Illustrative quotes	
Thematic Category 1: Most Frequent Learning Methods to Resolve Unplanned Design Iterations	The interviewees frequently referred to prototyping, experimentation, testing, proof of concept, outsourcing and assistance from technical experts. However, in general, the companies lacked a proper selection criterion for the most suitable learning methods to resolve unplanned design iterations	*'we have several SLA (stereolithographic apparatus) machinery for building prototypes in very high quality. So, this is something that we have a high focus on it'* (C1-C)	*'if we have three possible solutions to a problem, then we often just have to select one of them that we believe in, and sometimes pick the wrong choice'* (D2-D)
Thematic Category 2: Learning from Mistakes and Failures in NPD Process	The data analysis indicates that most companies lacked a structured process for converting knowledge from failures and mistakes into organisational learning. On the other hand, the health care company (D) used a special task force to secure the new knowledge and transfer it to other projects	*'we have tried (to establish a process), but we don't have a consistent process for our lessons learned, and it is something that is on the table. There is a framework to do that, but that framework is currently not running'* (C1-C)	*'we have tried to make databases on this (to secure knowledge), and it ends up in not being used. People are so busy with the projects, so they don't use all this stuff. What we instead do is that we try to circulate people between projects, bringing knowledge from one project to another'* (D1-D)
Thematic Category 3: Most Frequent Unplanned Design Iterations	Generally, during the NPD projects, the engineering design teams could not reduce the unplanned design iterations regarding changing requirements and complexity of the product. The unplanned design iterations impacted the timeline and development cost of the NPD projects	*'I use very active risk assessment (in the design phase) and I think it's become apparent also to others that it's a pretty effective way of working'* (D2-D)	*we try to have these (risk monitoring) meetings regularly and you create risk reports and so on. And basically, I have found it very, very difficult to make that work'* (G1-G)

5. Discussion

To our knowledge, this is one of the few empirical studies that has been done to explore how organisations employ 'proactive risk management' (PRM), and 'reactive fast learning' (RFL) approaches for managing unplanned design iterations in NPD process. In this empirical study, we identified several insights that were consistent with past research. While utilising PRM, the engineering design teams maximised their focus on identifying and mitigating the unplanned design iterations risks traditionally in the conceptual phase and informally in the design phase of the NPD process (Wynn, Eckert, and Clarkson 2007, Meier, Yassine, and Browning 2007); the design teams could not identify few unplanned design iteration risks (Thamhain 2013, Beauregard 2015); and the triggers of unplanned design iterations identified during the study were predominantly changing requirements, lack of knowledge and human errors (Eppinger 2001, Krehmer, Meerkamm, and Wartzack 2009, Mujumdar and Maheswari 2018, Unger and Eppinger 2011). While employing RFL, the engineering design teams used various learning methods for fast resolution of unplanned design iterations (after their occurrence) specifically prototyping, experimentation and simulations (Shafqat et al., 2019a).

However, for many (but not all) study participants, several additional issues also influenced the practices of PRM and RFL in managing the unplanned design iterations. In particular, several study participants placed a high focus on using learning methods (along with other risk mitigation strategies) to mitigate unplanned design iteration risks prior to their occurrence; the engineering design teams were more active in risk monitoring in the design phase than in the concept development phase; mostly engineering design teams did not use many of the risk assessment tools which are recommended in ISO standards (IEC 31010 2009); some companies did not provide enough resources for risk assessment; organisations lacked a structured approach to select the most appropriate 'learning methods' for resolving unplanned design iterations after their occurrence; organisations lacked structured approach to capture new technical and process knowledge for the use of future projects.

Previous studies have emphasised on the early detection of potential design iterations in the conceptual phase of the NPD process (Wynn, Eckert, and Clarkson 2007, Meier, Yassine, and Browning 2007). While using the PRM approach, we also found that engineering design teams were focusing on the prediction of unplanned design iteration risks. What our study adds to this view is the recognition of the need for 'active' risk monitoring in the detailed design phase to maximise the likelihood of predicting unplanned design iterations before their occurrence. For instance, for risk monitoring in the design phase, this study shows that the design teams held informal meetings and used brainstorming sessions to identify potential unplanned design iteration risks. They showed more ownership to risk monitoring in later stages as compared to the risk assessment phase at the start of the project.

In contrast to previous reports (Thamhain 2013, Beauregard 2015) indicating a limited capability of the risk assessment phase to identify many foreseeable risks, this study reports that the risk monitoring phase identified most of the foreseen unplanned design iteration risks which were missed in the risk assessment phase. For instance, to monitor unplanned design iteration risks, project managers held regular informal meetings with engineering design teams. Therefore, overall, the PRM approach performed better in an industrial perspective for identifying unplanned design iteration risks except for a few re-occurring risks in the design phase. One interpretation of this variation is that the risk monitoring in later stages might be convenient for design teams due to the availability of more information and less uncertainty in the later stages of the NPD process. Such as, see, e.g., Oehmen and Seering (2011) reported that the NPD process does not focus on reducing uncertainty despite its capability.

Previous studies have reported the use of various risk mitigation strategies to reduce the likelihood of the occurrence of the risks (Hsiao et al. 2016, Abdul-Rahman, Mohd-

Rahim, and Chen 2012). This study also indicates that various risk mitigation actions were used to reduce the occurrence of unplanned design iteration risks. However, this paper adds another dimension to risk mitigation actions by reporting the use of 'learning methods' as risk mitigation actions for reducing the likelihood of the occurrence of unplanned design iteration risks. For instance, the engineering design teams used prototyping and experimentation to reduce the likelihood of occurrence of the unplanned design iteration risks. This helped the design teams in reducing technical design uncertainty which ultimately led to the reduction of unplanned design iteration risks. The results also indicate that some of the unplanned iterations occurred despite the utilisation of risk mitigation strategies to reduce the unplanned design iterations. For instance, an R&D director stated that the projects in his company faced unplanned design iterations due to product complexity.

Unlike many other comparable studies, this paper did not focus on 'planned' design iterations. This enabled us to explore the approaches (PRM and RFL) for managing only unplanned design iterations both before and after their occurrence. The findings from this study indicate that the RFL approach is less established and structured as compared to the well-established PRM approach for managing unplanned design iterations. For instance, the design teams employed learning strategies to resolve unplanned design iterations. Still, they were unable to select the most efficient learning methods for fast resolutions of the unplanned design iterations. For instance, a project manager had three (learning method) alternatives to resolve unplanned design iterations, but he selected (a learning method) alternative based on his gut feeling. A possible explanation for this may be the lack of adequate experience of the design teams and lack of resources available to choose alternative learning methods.

The theory of single-loop learning and double-loop learning (Argyris and Schön 1997) highlights the importance of using learning and capturing new knowledge for the progress of future NPD projects. Apart from one organisation in the study, the findings from our study demonstrate that organisations, in general, lacked a structured approach to capture the new knowledge including process and technical knowledge while resolving the unplanned design iterations. Our study also reveals that companies were overall better in single-loop learning as compared to double-loop learning. For instance, a project manager (C1-C) mentioned that his organisation has the system to capture new knowledge, but it's not functional, and the organisation was unable to use the new knowledge in future projects. One possible interpretation of this might be the lack of motivation or incentives for the design teams to report new knowledge. They might consider this task as an extra burden and focus on their technical tasks only. This might also be the possibility that the organisations did not provide enough resources to establish a reporting system for new knowledge.

The findings from this study have significant implications for the organisations involved in NPD projects. The failure rate of NPD projects is very high (Barczak, Griffin, and Kahn 2009) and undesirable design iterations are one of the reasons for the failure of NPD projects (Ballard 2000). The management of unplanned design iterations (which are often undesirable) before and after their occurrence is an immensely important intervention for all organisations involved in NPD projects, but particularly with a high failure rate of the NPD projects. Design teams must manage unplanned design iterations efficiently. This includes minimising the likelihood of unplanned design iteration risks and fast resolution after their occurrence. Our study suggests that along with the prediction of unplanned design iterations, the fast resolution of unplanned design iterations using efficient learning methods is a crucial part of managing the unplanned design iterations. But the design teams may fail to manage unplanned design iterations (efficiently) after their occurrence without adopting a structured approach to select the most efficient learning methods.

6. Conclusion

6.1 Contribution

The purpose of the current paper was to close the significant gap on exploring the practices of 'proactive risk management' PRM and 'reactive fast learning' (RFL) for managing the unplanned design iterations by product development organisations. For this, we investigated the research question: How do organisations employ both PRM approach, as well as RFL approach, to manage unplanned design iterations in the NPD process? As an answer, we presented empirical findings on how organisations manage unplanned design iterations using PRM and RFL approaches.

The most prominent finding to emerge from this empirical study is that PRM approach is well established as compared to RFL approach for managing unplanned design iterations. The research has also shown that, while employing PRM, the engineering design teams were more active for risk monitoring in design phase as compared to the concept development phase. For resolving the unplanned design iterations after their occurrence, the engineering design teams lacked a structured approach for selection of the most suitable learning methods. This finding suggests that, while employing RFL approach, it is essential to consider the most efficient learning methods (as already explained in theory and result sections) according to the categories of unplanned design iterations. One of the more significant findings to emerge from this study is that organisations failed to convert the new technical and process knowledge (gained during resolution of unplanned design iterations) into organisational learning. To avoid the unplanned design iteration in future NPD projects, this study suggests that it is vital to secure new knowledge and use it in future NPD projects through organisational learning.

6.2 Limitations

There are a number of limitations which affect the findings of this paper and should be considered for future research. First, the interview study was conducted in the organisations only headquartered in Denmark. The description of PRM and RFL practices to manage unplanned design iterations is likely affected by certain Danish cultural aspects. Therefore, this might limit the generalizability of the results in this paper. Second, we might have been affecting the interview study by our bias unwittingly, e.g. through questionnaire formulation, sample selection, or pushing specific aspects of the study during interviews. To avoid socially desired answers, we asked the same question in different ways. However, as in any interview study, the respondents might have given biased answers for unknown reasons. Finally, we conducted the interview study primarily in the engineering companies which might be extended to a broader context.

6.3 Future Research

For future research, we have identified the two most significant findings from this paper as possible research topics. First, using the findings from this paper, future research should consider outlining a structure in the selection of the most efficient learning methods for resolving unplanned design iterations according to their specific category. Second, future research might consider studying why engineering design teams are more active in monitoring unplanned design iteration risks in the design phase than in the NPD process's concept development phase.

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Appendix. List of Open-ended Interview Questions

The following questions give an idea about the type of questions asked during the interview study. Due to the study's exploratory nature, we used 'snowballing' (Bell, Bryman, and Harley 2018) as the sampling strategy during the interviews. Therefore, we started the interviews with the questions given below but did not stick to the questionnaire. We asked, "what if" questions to find out the participant's perceptions about managing unplanned design iterations by using "proactive risk management" and "reactive fast learning".

1. Introduction

- What is your role in the product development process (PDP)?

2. NPD Project Description

- In which type of NPD projects are you involved in the company?
- What is the (progress) status of the NPD project?
- Which type of engineers (e.g., mechanical, mechatronics, electronics, software, etc.) are involved in the NPD process design phase?

3. Risk Management and Key Risks in Design Phase

- Do you practice the traditional risk management process?
- Do you employ risk management experts to identify risks?
- Do you monitor design risks continuously?
- What are the major risks (technical, market and organisational) and type of uncertainties in the design phase of NPD process?
- Can you please give us an example of major risk, uncertainty, or design rework in the NPD process design phase?
- How do you mitigate the design risks?

4. Unforeseen Risks in Design Phase

- Can you please give us some examples of major design tasks in the design process that were particularly uncertain?
- Can you please give us examples of unforeseen design risks that occurred during the PDP?
- What are the causes of unforeseen design issues that caused design rework?

5. Learning Methods and Unexpected Design Challenges

- How do you react to manage unexpected design challenges?
- How do you learn about solutions to unexpected design challenges?
- Do you get help from experts and learn from their experience for managing unexpected design challenges?
- Were you prepared to manage unexpected design challenges?
- Can you give us some examples of "methods" used to solve unexpected design issues during the PD process?
- What makes these "methods" useful to you? What were the methods that were not useful, and why?

6. Learning from Failures and Mistakes

- Do you learn from failures and mistakes in the design phase?
- Do you have some organisational structure to capture new knowledge gained during the problem-solving process?
- Do you learn from managing unexpected design iterations to manage design challenges in future projects?

7. Proactive Measures and Unexpected Design Challenges

- If you could go back on time and meet yourself at the beginning of the design phase, what would you tell your younger self? Why?

Paper D - Empirical Investigation on the Role of Risk Mitigation Actions in Engineering Projects

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