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

**Shafqat, Ali; Welo, Torgeir; Oehmen, Josef; Willumsen, Pelle Lundquist; Wied, Morten**

*Published in:*
Procedia CIRP

*Link to article, DOI:*
10.1016/j.procir.2019.04.248

*Publication date:*
2019

*Document Version*
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 84 (2019) 412–418

www.elsevier.com/locate/procedia

29th CIRP Design 2019 (CIRP Design 2019)

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

Ali Shafqat[a]*, Torgeir Welo[a], Josef Oehmen[b], Pelle Willumsen[b], Morten Wied[b]

[a]*NTNU - Norwegian University of Science and Technology, Mechanical and Industrial Engineering, Richard Birkelandsvei 2B, N-7491Trondheim, Norway*
[b]*DTU - Technical University of Denmark, Department of Management Engineering, Engineering Systems, Produktionstorvet, 2800, Kgs. Lyngby, Denmark*

* Corresponding author. *Tel.:* +47-998-74-620; *E-mail address:* ali.shafqat@ntnu.no

**Abstract**

Product development (PD) faces uncertainties caused by rapidly developing technologies, shifting market demands and the changes occasioned by these developments, including new requirements for products being developed and increased difficulty for companies 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, which assumes that organisation members involved in PD have sufficient time and resources to identify, analyse and mitigating technology risks and organisational risks. However, the reality of product development is that time and resources are rarely sufficient, and uncertainty is currently being introduced to the development process at an accelerated rate by trends such as pervasive digitalisation. This paper therefore investigates a resilience-inspired approach to PD risk management that abandons the predict and plan paradigm in favour of a 'monitor and adapt' approach. We argue that, in industrial practice, predict and plan approach is the de facto risk management baseline, and suggest deliberately tailoring risk management and PD processes to incorporate resilience-based practices. To that end, we provide suggestions for process frameworks and tools organisations may adopt and discuss how resilience and risk management are complementary approaches to traditional PD. Our arguments are supported by a case study of an engineering organisation and additional interviews conducted with members of similar organisations for purposes of 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, companies that face high levels of competition experience additional pressure to introduce new products in order to capture new markets. New product development (NPD) processes involve significant amounts of risk. A study indicates that only 15% of new product ideas, and around 60% of NPD products, achieve commercial success in the market [2]. The success of NPD projects is usually measured by the length of lead and development time, the cost of the project and the ability of the project to satisfy customer demands. However, NPD projects face obstacles that can contribute to risk, such as the possibility of cost and time overruns and even failure to achieve desired product performance [3].

There are various definitions of risk found in the literature on NPD; for instance, the ISO 31000 defines risk as the 'effect of uncertainty on achieving NPD objectives' [4]. The risks associated with the product development process (PDP) include technology risks, market risks, collaborative risks and financial risks [5]. It is typically beneficial for companies to address risks and uncertainties during the early design phase of product development (PD), because the early assessment of risks can reduce the overall cost of mitigation efforts, as is illustrated in Fig. 1 below [6]. Risk levels are generally very high at the start of a project, but the cost of making changes that reduce risk and reduce the likelihood of undesirable events is much lower during this period than it is at later

2212-8271 © 2019 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the CIRP Design Conference 2019.
10.1016/j.procir.2019.04.248

stages, as Fig. 1 also shows [6]. Risk management strategies are often applied to identify, control and ultimately mitigate levels of risk in PD projects [4,6]. Strategies that seek to manage risk in this way adopt what can be called the 'predict and plan' risk management approach.

Firstly, the predict and plan risk management approach places the maximum emphasis possible on identifying risks and quantifying the possibility that negative outcomes related to these risks occur. Secondly, this approach plans in order to mitigate the impact of the identified risks. For example, after risk identification, analysis and assessment are carried out at the start of an NPD project, appropriate risk mitigation measures are planned [6]. This predict and plan approach is a typical strategy for mitigating risk in risk management processes applied to NPD projects. However, the literature indicates that a large amount of risk is not identified until after performance has already been negatively affected [7], or alternatively, though risk is identified, it is not addressed properly [14].

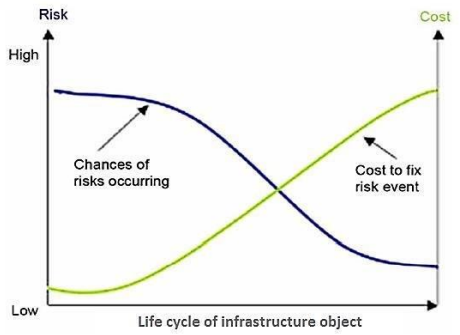


Fig. 1. Cost and risks in project lifecycle (adopted from [6]).

Schuh et al. [5] and Oehmen et al. [8] argue that current PD strategies and approaches are not fully capable of addressing changes that must be made within the PDP to manage risk [2,8]. Risks arising in the PDP are often addressed reactively instead of through proactive risk management strategies [9]. The reactive approach to risk management can be called the 'monitor and adapt' approach; an example of this is the case in which design engineers face unexpected design problems in the design phase of the PDP, and they try to find possible solutions to the problems that are effective in the short term. The design engineers monitor the situation and try to adapt accordingly. Aven [10] argues that, in general, risk management and resilience management complement each other, pointing out that resilience analysis and resilience management are today well-integrated into the field of risk studies. We therefore hypothesise that the ability of a company to identify, analyse and mitigate the technology related risks, requirement risks and organisational risks that arise within the PDP may be enhanced overall by introducing resilience-inspired approaches to PD risk management.

Resilience is the ability of a system to sense, recognise, absorb and adapt to changes, disturbances, variations, surprises and disruptions [11,12,28]. Within an approach to PD, focusing on resilience involves ensuring the availability of 'post-surprise' options with the assumption that surprises in the process are inevitable.

The field of resilience studies is currently developing at a fast pace and finding applications in an increasingly wide range of disciplines, particularly in the areas of security and infrastructure [10]. The concept of resilience was introduced to discussions around the field of engineering by the safety engineering community [11], a relatively new area in the engineering field [12]. By enhancing the resilience of a system, the safety of the system can be improved without performing risk calculations [10]. In a traditional risk assessment process, it is necessary that risks be quantified by means such as the modelling of impact-probability distributions. In a resilience approach, that is not strictly necessary [10].

In this paper, we follow the argument made by Aven [10] that is cited above in order to develop a holistic approach integrating risk- and resilience-based thinking and apply it to PD. As is defended by Aven [10], this approach encourages thinking of risk management and resilience perspectives as complementary to each other. On the one hand, to give proper direction to a resilience-based strategy, it is necessary to implement a risk analysis framework. On the other hand, however, resilience-based strategies add reactive and adaptive capabilities to a process that are not represented by risk management approaches alone. We apply this argument to PD and assess the potential for an approach that combines resilience and risk management to improve the speed, cost-effectiveness and technical quality of the PDP.

The remainder of the paper is organised as follows: section 2 explains the research method that was used to conduct the study; section 3 describes the standard risk management framework and the shortcomings of existing approaches; section 4 introduces the resilience approach and describes how it is applied to deal with unknown risks in the PDP; section 5 presents the findings of a qualitative case study and interviews that were conducted for the present work; section 6 analyses and discusses the way in which classic risk management and resilience are applied together in PD projects; finally, section 7 presents the study's conclusion.

## 2. Method

The nature of the research presented in this paper is exploratory, as we seek to empirically understand and establish the relationship between resilience and risk management applied to product design and development. The research approach is predominantly deductive [31]; the research method most suitable to the present work is thus that of the case study [13]. In the case study conducted for this work, we investigated an ongoing PD project in which we the researchers had no control over the environment. The exploratory character of this study made interviewing a suitable primary method of data collection.

Three companies (referred to in what follows as P1, P2 and P3) provided data for this study. For the purposes of the case study, company P1 provided access to project documentation and allowed us to speak to members of the company's design team, product management and program management. Meanwhile, companies P2 and P3 facilitated contact with project managers with whom we were able to carry out

additional interviews. All three organisations are large international companies in the medical industry with their headquarters in Denmark.

The case study focuses on one PD project in particular (Project1 of company P1); to collect detailed information concerning the project, we conducted interviews with the project managers and design engineers. As mentioned above, we also conducted interviews in two other companies (P2 and P3) to provide additional insight beyond the findings of the case study. Design engineers made for desirable interviewees because they tend to have personal views regarding project success and play a distinct role in risk management and resilience. As stated above, additional information for the case study of company P1 was gathered in the form of documentation related to Project1, allowing for a detailed study of the project. We recorded all interviews and wrote out complete transcripts; the duration of each interview was between 45 and 60 minutes.

We conducted semi-structured interviews [31], and strove to achieve consistency and reliability by using in each interview an interview script that established the particular topics to be addressed. The interview script included a combination of open and closed questions focusing on three topics: how risk management was performed in the company's PDP; why risk management failed to control risks in the PDP; and how resilience-based practices enhanced the company's ability to address unknown risks in the PDP. The analysis of the responses was carried out by means of pattern matching [13]. A coding scheme was developed based on a review of the literature on risk management and resilience (presented in sections 3 and 4). We identified instances where predict and plan and monitor and adapt approaches were exemplified, as well as instances where risk management principles, such as risk identification, and resilience principles, such as adaptability, were discussed.

## 3. Risk Management in Product Development

In the context of PD, risk management refers to the process of uncovering and managing risk in the PDP. The risk management process follows a structured approach and aims to initiate mitigation actions in a timely manner that help avoid, transfer or reduce risk likelihood or impact [15]. Herrmann [16] lists the following key steps in risk management processes:

- 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 encompassing the steps of risk identification, risk analysis and risk evaluation. Risk assessment allows a company to improve their understanding of the risks of a process and to identify suitable approaches for risk treatment [30]. The risk assessment phase of the risk management process also implements suitable tools and techniques during the life-cycle phases of a PD project. During the design and development phase of a PD project, for example, risk assessment seeks to improve the design refinement process and cost-effectiveness of the PDP, as well as to ensure that the overall system risks of the PDP are tolerable [30].

The tools and techniques that are typically used in the risk assessment phase of the risk management process are well-known, and can be found listed in Table 1 [30]. The tools and techniques that should be applied vary according to the stage of risk assessment. As Table 1 illustrates, for example, the technique of primary hazard analysis is strongly applicable for risk identification, but is not useful for analysing and evaluating identified risks. Meanwhile, root cause analyses are not applicable to the stage of risk identification in PD projects, but are strongly applicable to risk analysis and evaluation.

Keizer et al. [17] have found that traditional risk management techniques are inadequate for controlling risks in PD projects. Traditional risk management techniques include fault tree analyses, event tree analyses and failure mode and effects analyses, all of which are included in Table 1. It should be noted that the tools and techniques that are listed in Table 1 are typically used in predict and plan approaches, and thus seek to identify the potential risks in PD projects. The identified risks are then analysed and evaluated to determine what further risk mitigation planning is necessary. One drawback of implementing a predict and plan approach in a PD project is that, in an uncertain project environment, a company will not be able to control risks that are not predicted. Thamhain [7], for instance, argues that a large number of risks are generally not predicted in the risk assessment phase, and these risks affect project performance in the later stages of the PDP.

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

| Tools and techniques | Steps of 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 [30]

### *3.1 The development process for products with diverse risk characteristics*

The PDP can involve many risks depending on the type of product chosen for development [18]. PDPs tend to range from processes that are highly rigid and controlled to more flexible approaches [19,20]. The specific risks involved in a PDP and the mitigation strategies that must be applied are determined by the type of product being developed, as well as the relevant market situation and the time and budget available for the process. Table 2 summarises the major technical, marketing, schedule and budget-related risks involved in an ordinary PDP.

In the PDP, these types of risk represent major risk categories according to Unger and Eppinger [18]. These categories of risk may be further divided into subcategories that are specific to particular companies and projects [18].

Table 2. Major risk categories in the PDP.

| Major risk type | Causes [21] | Type of PDP suitable for mitigating risk [18] |
|---|---|---|
| Technical | Vague design specifications; risk is 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 and underestimation in budget planning | Design- to-budget |

## 4. Resilience in Product Development

The contemporary concept of resilience that is applied and studied today was proposed by Holling [22] to describe ecological systems that persist in unpredictable environments. In this work, Holling [22] made a fundamental distinction between systems designed for stability and systems designed for resilience.

From the study of natural systems, Holling [22] drew two conclusions relevant to the management of man-made systems: firstly, important, unexpected events will always occur, regardless of the sophistication of the up-front planning of the system; secondly, instead of aiming to predict future events, systems should develop their capacity to absorb and accommodate unforeseen events in whatever form they may take.

Since its inception, resilience thinking has been applied to a wide range of businesses settings, including supply chains [23], business models [24] and the overall organisation of businesses [25]. Bringing resilience thinking closer to the field of PD, Crosby [26] has defined project resilience as 'the ability to recover from, or adjust easily to, misfortune or change'. Working in the same area, Kutsch et al. [27] have distinguished resilient project management from what they call 'rule-based' project management, also known as 'stability-focused' project management; this distinction is illustrated in Fig. 2 below.

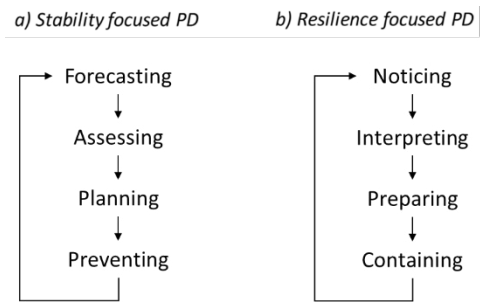


Fig. 2. Two contrasting managerial principles (adopted from [27]).

In an attempt to operationalise and clarify the concept of resilience, Carpenter et al. [29] have posed the question 'Resilience of what to what?', understanding 'of what' to correspond to system performance and 'to what' to system uncertainties. Applied to PD, the category of system performance includes the cost and time of development and the quality of the product, while system uncertainties include the major risks (listed in Table 2) that threaten to influence the cost and time of development and the quality of the product.

## 5. Results

This section presents the results of seven interviews conducted with design engineers and project managers of three organisations (P1, P2 and P3). In what follows, the designations PM1, PM2 and PM3 represent project managers interviewed from P1; DE1 and DE2 represent design engineers from P1; and PM4 and PM5 represent project managers from P2 and P3, respectively.

### *5.1 Risk management practices*

The design engineers and project managers of the three PD organisations expressed similar opinions regarding the use of risk management to identify and address risks in the early phase of the PDP. To identify risks, all project managers and design engineers reported using brainstorming techniques, as listed in Table 1, in the early phase of their PD projects. Referring to the risk assessment measures taken in Project1, DE2 recalled, 'we tried to sit down with key individuals in order to risk assess a new project, and that was actually done before the full project was started'. Each of the three PD organisations (P1, P2 and P3) implemented a predict and plan approach to control the risks in the design phase of their projects. PM5, a project manager in the organisation P3, said that, in general, 'the members of the organisation always try to predict problems, but I think that type of activity is quite often difficult'.

The project manager PM4 of P2 stated that, in the development of their organisation's project, risk management practices are not viewed as particularly important, and are not prioritised by management. Some of the design engineers and project managers who were interviewed also described ways the predict and plan approach had failed in their projects. PM4 for example, commented, 'but the thing is, every time stuff [doing risk management] takes too long, [and] then we don't do it unless we have to'. PM4 also stated that, 'when risk

management is implemented, it involves a lot of stuff that people go around [thinking] about, and [they] say, "Okay, this might be a risk", instead of writing it down. And the main risks that are being written down'.

The project managers in all three companies identified the major risks in their organisations' PDPs as the occurrence of time-to-market delays and excessive project development and product manufacturing costs. The project manager PM5 of P3 stated that, in past projects, the organisation '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 reportedly did not make resources available for risk mitigation planning in the project. PM5 of P3 reported, '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), design engineers reported that in their projects they implemented proof of concept testing for high-risk design tasks as a risk mitigation strategy. PM1 of P1, for instance, stated that, in a given project, 'all the unknowns are major risks, and my approach is the proof of concept for all the unknowns'. The design engineer DE2 of P1 defended this approach, stating, 'if we have more prototypes, then we have [fewer] risks'. In all three organisations' projects, surprises occurred that were not identified during the early risk assessment phase of the PDP.

### *5.2 Resilience practices*

Although the design engineers and project managers we interviewed did not explicitly refer to 'resilience practices', their responses indicated that they nevertheless carried out resilience-focused actions in their projects when responding to unanticipated risks and surprises.

Company P1, for instance, on which our case study focused, implemented a resilience-focused approach in their project. The statements of DE1 and DE2, design engineers of P1, for example, indicated that the measures the company took to handle 'unexpected design issues' served to improve the resilience of the PDP. DE1 noted that 'if something [in the design process] needs to be escalated, we have direct access to company owners. That's one area which makes the company better'. The design engineer added that 'the whole reason why this company is where [they are now] is that they move so quickly, [and that is why they have] been market leader'. The interviewees' responses also indicated that company P1 applied a monitor and adapt approach to handle surprises occurring in the design and development phase. PM1 of P1, for instance, reported that he had weekly meetings with his team to get feedback from them, which allowed him to continuously monitor risks and surprises that emerge in the design phase.

The responses of PM4 of P2, meanwhile, suggested that the company did not regularly carry out resilience-based actions in response to surprises in the design phase because of a lack of readiness for such actions. PM4 recalled how, as the result of surprises in the design phase of the project, the organisation was 'all of a sudden going from only having to develop one product [to needing] to develop six products in a very, very short amount of time', a task the company was not prepared for.

PM5 of P3 described actions taken by P3 to enhance resilience capability, in particular the engaging of experienced human resource professionals in the PD project. PM5 reported, 'if we had a severe problem on a project, we had this kind of taskforce you could call it, key individuals that we could [direct] to that problem, which would increase the likelihood of succeeding on that given problem'.

Taken together, the responses of the interviewees suggest that risk management practices were better formalised in the PDPs of the three companies we studied than resilience-based practices.

## 6. Analysis and Discussion

The results presented in section 5 include statements made by project managers and design engineers from the companies P1, P2 and P3 concerning the risk management and resilience practices they implement and how these influence the progress of PD projects. As was mentioned earlier in the paper, we are adopting a theoretical perspective informed by Aven's [10] view of risk management and resilience as complementary to one another, allowing organisations to simultaneously manage known and unknown risks; a similar argument is also made by Oehman and Seering [28].

In the case study of a project (Project1) of company P1 that was carried out for the present work, the team members PM1, PM2, PM3, DE1 and DE2 agreed in their assessment that Project1 was delayed due to poor risk assessment by product management in the early stage of the project. One year after the project was started, product management made a decision to split Project1 into two separate projects. As PM1 recalled, '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 [of poor risk assessment], the [management] splitting [the] project into two'. In this case, one can fairly attribute the company's inability to identify the risk involved in the project and failure to develop a plan to mitigate the risk which is an example of an inappropriate predict and plan approach. At the same time, the decision to split the project into two is an example of a resilience approach aiming to adapt to the changes and surprises, as management delayed the decision for one year and then made it necessary to develop new PD goals. In this project, time to market was identified as a success criterion for the PD project; it is also a threshold parameter for resilient systems. As DE2 stated, 'just time is costly [in this project]'. After splitting the project in two, the project manager implemented a monitor and adapt approach, using proof of concept testing for all unknowns in the project. Proof of concept testing is a technique aligned with the resilient approach because it addresses unknown risks that cannot be accounted for in a predict and plan approach. PM1, who, as is mentioned above, stated that 'all the unknowns are major risks and my approach is the proof of concept for all the unknowns', implemented the resilience-focused practices of observing, responding and rebounding, as is represented in

Fig. 2. DE2, it is worth noting again, provided an argument in favour of PM1's approach, saying 'if we have more prototypes, then we have [fewer] risks'. Predict and plan approaches and associated practices such as frontloading can improve regulatory aspects of a PD project. Speaking of Project1, PM2 stated, 'we actually succeed [in] involving him [individual with knowledge of regulatory affairs] a lot, also in the initial planning phases. And [these phases are] a really, really crucial part because it's where actually compliance [decisions] can have an impact on the scope [of the project]'. This statement also highlights the overlap between the predictive capacity of an approach and its robustness, as the involvement of an individual with knowledge of regulatory affairs allows the organisation to identify potential vulnerabilities that may create unanticipated problems later. Risk management and planning are often perceived as connected in practice. In the case study, the predictive element of risk management was clearly recognised by project personnel. PM3, for instance, stated, '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 [trying] to plan accordingly'.

The project manager PM4 of P2 mentioned in his interview that risk assessment was not a priority for him, stating 'but the thing is every time stuff [doing risk management] takes too long, [and] then we don't do it unless we have to'. The predict and plan approach was therefore poorly executed in past PD projects in P2. As PM4 noted, 'in the project that I am [in] now, we try to be proactive, but I think the main approach has been reactive for the many years [I have worked here]'. The PD project in which P2 was engaged at the time of the study became subject to scope creep, which was a significant unexpected event for design engineers. PM4 also discussed how, in the project, the organisation was 'all of a sudden going from only having to develop one product [to needing] to develop six products in a very, very short amount of time'. PM4 began applying a monitor and adapt approach later in the project and resilience-based practices such as proof of concept testing in order to 'get into how can we make sure that it's easy to prove that [the product] works'. Overall, P2 thus implemented a mixed approach in their project.

PM5 of P3 used a brainstorming technique, as listed in Table 1, to identify risks. Product management in P3 tended to apply risk assessment-based planning to manage identified risks in past and present PD projects. PM5 noted, however, that 'they [product management] always try to predict problems, but I think that type of activity is quite often difficult'. PM5 also implemented practices allied with a resilience approach, calling, for example, upon experienced designers to solve a specific design problem in order to regain stability, a practice reflecting the resilience approach as presented in section 4. PM5 reported that similar actions were taken to address other types of problems, recalling, '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 Project1 and past projects of company P1, product management implemented both predict and plan and monitor and adapt approaches. The predict and plan approach, which involves risk management practices, focused on proactive measures that could be taken to avoid risks in the PDP, while the resilience-based approach addressed the 'reality aspect' of the PDP by seeking to reduce the impact of the potential unknown risks in an uncertain PD environment. The interviews with members of two additional companies, P2 and P3, validated the notion that risk management and resilience complement each other.

A resilience-based approach has the advantages of agility and robustness; in other words, resilience practices allow companies to respond effectively to unexpected events and absorb variations in the process. Meanwhile, the application of risk management to PDPs contributes to robustness because it involves proactive planning in order to avoid variations in the process. On the other hand, however, risk management lacks agility because it involves planning that is based mainly on known risks and their known probabilities; risk management thus does little to improve the resilience of a PDP. An approach that overlaps resilience-focused practices with risk management practices is therefore optimal for PD projects.

## 7. Conclusion

The study presented in this paper evaluated the hypothesis that risk management and resilience-based approaches complement each other in managing risks of PD projects. This hypothesis was confirmed in our case study of the project of company P1 and in the additional interviews we conducted with members of companies P2 and P3.

To address known and unknown risks, the company P1 on which the case study focused used both predict and plan and monitor and adapt approaches in their PD project. Product management in all three organisations predominantly implemented either a predict and plan approach or a monitor and adapt approach to mitigate the impact of unknown risks and surprises in their PD projects. The analysis of the empirical data we collected indicated that risk management and resilience approaches complement each other as a strategy to address both known and unknown risks. The analysis also revealed that the predict and plan approach is well-established in the three companies we studied, while the resilience-based monitor and adapt approach is less established as a strategy for handling surprises in the design process.

In light of the study of the literature and analysis of the empirical data presented in this paper, we suggest that by overlapping risk management and resilience approaches organisations can better avoid and mitigate the impact of known and unknown risks in PD projects.

The present paper appears to be the first exploratory empirical study conducted concerning the implementation of a resilience-inspired approach in PD risk management. To generalise the resilience-inspired PD risk management approach to other PD projects, we recommend that further empirical studies of this topic need to be conducted.

## References


[1] McDermott CM, O'Connor GC. Managing radical innovation: an overview of emergent strategy issues. Journal of Product Innovation Management: An International Publication of the Product Development & Management Association. 2002 Nov;19(6):424-38.

[2] Barczak G, Griffin A, Kahn KB. Perspective: trends and drivers of success in NPD practices: results of the 2003 PDMA best practices study. Journal of product innovation management. 2009 Jan;26(1):3-23.

[3] Francis P, Golden M, Woods W. Defense acquisitions: managing risk to achieve better outcomes. Government Accountability Office Washington DC; 2010 Jan 20.

[4] ISO 31000:2009 Risk management – Principles and guidelines. Geneva. Available at: http://www.iso.org/iso/home/standards/iso31000.htm.

[5] Schuh G, Gartzen T, Soucy-Bouchard S, Basse F. Enabling agility in product development through an adaptive engineering change management. Procedia CIRP. 2017 Jan 1;63:342-7.

[6] Lough KG, Stone R, Tumer IY. The risk in early design method. Journal of Engineering Design. 2009 Apr 1;20(2):155-73.

[7] Thamhain H. Managing risks in complex projects. Project management journal. 2013 Apr;44(2):20-35.

[8] Oehmen J, Olechowski A, Kenley CR, Ben-Daya M. Analysis of the effect of risk management practices on the performance of new product development programs. Technovation. 2014 Aug 1;34(8):441-53.

[9] Oehmen, J., Oppenheim, B.W., Secor, D., Norman, E., Rebentisch, E., Sopko, J.A., Steuber, M., Dove, R., Moghaddam, K., McNeal, S. and Bowie, M., 2012. The guide to lean enablers for managing engineering programs. Joint MIT - PMI - INCOSE Community of Practice on Lean in Program Management.

[10] Aven T. The Call for a Shift from Risk to Resilience: What Does it Mean?. Risk Analysis. 2018 Dec 10.

[11] Aven, T., 2017. How some types of risk assessments can support resilience analysis and management. Reliability Engineering & System Safety, 167, pp.536-543.

[12] Bhamra R, Dani S, Burnard K. Resilience: the concept, a literature review and future directions. International Journal of Production Research. 2011 Sep 15;49(18):5375-93.

[13] Yin RK. Case study research and applications: Design and methods. Sage publications; 2017 Sep 27.

[14] Ing YB. Surprises and cost overruns: a lean risk management approach to reduce surprises and address cost overruns in aerospace product development projects. In Proceedings of the International Annual Conference of the American Society for Engineering Management. 2015 (p. 1). American Society for Engineering Management (ASEM).

[15] Risk Management Standard AS/NZS 4360 (1999) Risk Management AS/NZS 4360, Standards Association of Australia, Sydney.

[16] Herrmann JW. Engineering decision making and risk management. John Wiley & Sons; 2015 Mar 19.

[17] Keizer JA, Vos JP, Halman JI. Risks in new product development: devising a reference tool. R&D Management. 2005 Jun;35(3):297-309.

[18] Unger D, Eppinger S. Improving product development process design: a method for managing information flows, risks, and iterations. Journal of Engineering Design. 2011 Oct 1;22(10):689-99.

[19] Erat S, Kavadias S. Sequential testing of product designs: Implications for learning. Management Science. 2008 May;54(5):956-68.

[20] Eppinger, S. and Ulrich, K., 2015. Product design and development. McGraw-Hill Higher Education.

[21] Wu J, Wu Z. Integrated risk management and product innovation in China: The moderating role of board of directors. Technovation. 2014 Aug 1;34(8):466-76.

[22] Holling CS. Resilience and stability of ecological systems. Annual review of ecology and systematics. 1973 Nov;4(1):1-23.

[23] Sheffi Y, Rice Jr JB. A supply chain view of the resilient enterprise. MIT Sloan management review. 2005 Oct 1;47(1):41.

[24] G. Hamel and L. Välikangas. The Quest for Resilience. Harv. Bus. Rev. 2003; vol. 81, no. 9, pp. 52–63.

[25] Burnard K, Bhamra R, Tsinopoulos C. Building Organizational Resilience: Four Configurations. IEEE Transactions on Engineering Management. 2018 Aug;65(3):351-62.

[26] Crosby P. Building resilience in large high-technology projects: Front end conditioning for success. International Journal of Information Technology Project Management (IJITPM). 2012 Oct 1;3(4):21-40.

[27] Kutsch E, Hall M. Project resilience: The art of noticing, interpreting, preparing, containing and recovering. Routledge; 2016 Mar 9.

[28] Oehmen J, Seering W. Risk-driven design processes: Balancing efficiency with resilience in product design. The Future of Design Methodology. 201; (pp. 47-54). Springer, London.

[29] Park J, Seager TP, Rao PS, Convertino M, Linkov I. Integrating risk and resilience approaches to catastrophe management in engineering systems. Risk Analysis. 2013 Mar;33(3):356-67.

[30] IEC 31010:2009. Risk Management. Risk Assessment Technique

[31] Bell E, Bryman A, Harley B. Business research methods. Oxford university press; 2018 Nov 5.