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towards a tentative theory

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DIGITAL-PHYSICAL PRODUCT DEVELOPMENT

TOWARDS A TENTATIVE THEORY

BY
STINE HENDLER

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Stine Hendler is an experienced management consultant and agile coach who has worked for a number of larger manufacturing companies. For 15 years she has focused on the product development process and its management. Her career builds on an engineering M.Sc. degree in International Technology Management with a specialisation in Global Business Development from Aalborg University. Stine has spent most of her time on the floor, solving real and urgent product development problems while maintaining a keen interest in the theoretical implications.

Stine is specialised within skills such as defining and executing improvement projects in product development, creating cross-functional collaboration in high complexity and high uncertainty projects, implementing agile methods in digital-physical product development, deploying strategy, facilitating agile social events, training agile practitioners, coaching project managers, product development teams and management.

ENGLISH SUMMARY

Manufacturing companies are increasingly enhancing their product offerings by adding digital functionality to their manufactured products. Such product digitalisation can significantly increase competitiveness, as software enables highly valuable functionality such as data storage and sharing, new customisation options and machine learning. However, engaging with digital product enhancements involves significant changes to the manufacturer's value chain. These changes pertain to key functions such as strategy, partnering, marketing, sales, distribution and product development.

This PhD thesis explores the consequences for product development within a large, mature and successful manufacturer, which is engaging with product digitalisation. Within this topic, the thesis explores a new field of research: the development of products that consists of both software and tangible product components, i.e. the digital-physical product development process, in which software development practices are combined with the development of physical products. More specifically, this thesis explores and summarises which practices and context effectively support digital-physical product development, how to effectively coordinate digital-physical product development, and how to effectively build this new capability within the manufacturer.

The study is based on a review of a scattered and emerging body of literature, upon which a research model is proposed. Using this research model as a guide, five successful digital-physical product development projects are studied, all five within the same case company. The data was collected over the course of six years. Combining case study and action research methods, the thesis documents in-depth insight and proposes tentative and descriptive theory in the form of 24 propositions.

The research results first establish that digital-physical product development involves separate subprocesses with different development practices. Digital development is optimised for adaptability via agile development methods with late and gradual binding of the product design. Physical development is optimised for stability via a firm-centric and linear development process with early binding.

The research finds that when combining a physical stability-optimised product development process and a digital adaptability-optimised development process, either the former process must become more adaptable, the latter must become less adaptable, or both need to change to achieve optimal performance of the overall process. As a key finding, the research demonstrates that it is *feasible for both* digital and physical to adapt to each other's development practices, though only to an extent. Implementing agile practices in physical product development is feasible to the extent

that it allows adherence to deadlines that have a high cost if they are delayed, for example, the Bill of Materials lock.

Digital-physical development also requires changes in product development practices. These include marketing strategies, becoming more focused on the external environment such as the competitor landscape developing new methods for testing, focusing on product architecture and organizing the project to include digital competences at all levels. Other changes to the development context involve changes to business models, marketing operations, post launch operations, quality acceptance criteria, product platforms, digital tools, and competences such as project governance and support functions.

The research also finds that effective digital-physical coordination involves *both* coordination in terms of standardisation of skills, process and output to accommodate the stability needed for efficient physical product development *and* involves agile coordination practices to allow adaptability.

Finally, the research finds evidence for an effective model for building new digital-physical product development capability. The model suggests that an initial digital-physical project is needed to collect learning about the new capability. With this experience, an effective and coordinated effort can subsequently be initiated, confidently prioritizing the most urgent capabilities for a first implementation wave. This coordinated effort can follow the steps of a structured problem solving process, while supporting and learning from ongoing digital-physical product development projects. Additional implementation waves can continue the maturation and completion of the needed capability.

DANSK RESUME

Flere og flere produktionsvirksomheder er i færd med at forbedre deres produkter ved at digitalisere dele af produkternes funktionalitet eller tilføre ny digital funktionalitet. Denne digitalisering kan medføre en markant forbedret konkurrenceevne, idet de nye produkter nu kan inkludere funktionalitet såsom dataopbevaring og deling, nye produkttilpasningsmuligheder til den enkelte bruger og maskinlæring. Sådan en produktforbedring, via digitalisering, medfører markante ændringer i en produktionsvirksomheds værdikæde. Ændringer er nødvendige i nøglefunktioner såsom strategi, partnerskaber, marketing, salg og produktudvikling.

Denne Ph.d.-afhandling undersøger netop konsekvenserne indenfor produktudvikling. Undersøgelsen finder sted i en stor, veletableret og succesrig produktionsvirksomhed, som er begyndt at digitalisere sine produkter. Hermed undersøger denne afhandling et nyt forskningsområde indenfor udviklingen af fysiske produkter, som også har digital funktionalitet, dvs. den digital-fysiske produktudviklingsproces, hvori softwareudvikling kombineres med udvikling af fysiske produkter i samme produktudviklingsprojekt. Inden for dette område undersøger og opsummerer denne afhandling, 1) hvordan man fra et procesperspektiv effektivt udvikler digital-fysiske produkter, samt hvilken virksomhedskontekst der bedst supporterer denne proces, 2) hvordan man effektivt koordinerer software og fysisk produktudvikling og 3) hvordan en produktionsvirksomhed effektivt kan opbygge den nødvendige evne til at udvikle digitale-fysiske produkter.

Undersøgelsen er baseret på et litteraturstudie af en fremspirende, men usammenhængende artikelsamling, som dog tegner et billede. På denne baggrund fremlægger afhandlingen en model med begreber og sammenhænge, som guider undersøgelsen af fem casestudier af succesfulde digital-fysiske produktudviklingsprojekter i samme case virksomhed. Dataindsamlingen foregår over seks år. Derudover benytter forskningen sig også af aktionsforskning, hvilket resulterer i en dyb indsigt. I alt fremlægges 24 hypoteser.

Forskningsresultaterne viser, at digital-fysisk produktudvikling indeholder digital og fysisk produktudvikling som to adskilte processer med forskellige udviklingsmetoder. Softwareudvikling er optimeret til at være tilpasningsdygtig gennem agile udviklingsmetoder, som tillader sene og gradvise beslutninger om produktdesign. Fysisk produktudvikling er optimeret til at være stabil, via ejerskab af store dele af værdikæden, samt en lineær udviklingsproces med en tidlig beslutning omkring produktdesignet.

Forskningsresultaterne viser også, at når man kombinerer digital udvikling, der er tilpasningsoptimeret og fysisk udvikling, som er stabilitetsoptimeret i samme projekt, så må enten den digitale udviklingsproces blive lidt mindre tilpasningsdygtig eller den

fysiske må blive lidt mindre stabil, eller begge må ændre sig for at optimere det kombinerede udviklingsprojekt. For at imødekomme disse komplikationer viser forskningen, at det er fordelagtigt, hvis både den digitale og den fysiske udviklingsproces ændrer sig, dvs. de tilpasser sig hinanden. Men kun i et vist omfang for at optimere den kombinerede proces. Helt specifikt er det fordelagtigt for en produktionsvirksomhed at implementere agile metoder i det omfang, at det ikke medfører forsinkelser af deadlines, som medfører store omkostninger, hvis de bliver forsinkede, såsom styklisten fra R&D til fabrikken.

Ligeledes viser forskningen, at digital-fysisk produktudvikling medfører ændringer i marketing strategier, produktarkitekturen, graden af ekstern orientering i virksomheden, metoder til produkttests, samt sammensætningen af digital-fysiske kompetencer i projektorganisationen. Andre ændringer i udviklingskonteksten omfatter forretningsmodeller, driften af marketingsudviklingen, drift af fasen efter lanceringen, kvalitetssikring, produktplatforme, digitale værktøjer, samt digitale kompetencer i, for eksempel, projektstyregrupper og supportfunktioner.

For at effektivt koordinere de digitale og fysiske udviklingsprocesser viser forskningen, at koordinering via standardisering af kompetencer, processer og output støtter den nødvendige stabilitet i fysisk produktudvikling, mens agile koordineringsmetoder støtter den nødvendige tilpasningsdygtighed. Dvs. en kombination af begge metoder er fordelagtig i digital-fysisk produktudvikling.

Slutteligt viser forskningen, hvordan en produktionsvirksomhed kan opbygge den nødvendige evne til at udvikle digitale-fysiske produkter. Denne opbygning indbefatter, at det første digital-fysiske projekt sættes i gang for at opsamle erfaringer. Med denne erfaring i rygsækken kan virksomheden effektivt udvælge og opbygge de nødvendige og mest presserende kapabiliteter i en første bølge. Et koordineret initiativ kan med gode resultater følge en struktureret problemløsningsmetode, samtidig med at det støtter og indsamler læringer fra igangværende digital-fysiske projekter. En sådan kapabilitetsopbygning kan fortsætte i adskillige bølger.

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CHAPTER 1. INTRODUCTION

1.1. THEME AND MOTIVATION

In 2012 I was working for a manufacturing company and sat next to a group of front-end product developers who were developing a radically different product. The project brief was to digitalise one of the company's physical products and test it in the market. In addition to developing a new version of the physical product the project involved developing software, new product usage patterns, new prototyping skills and new marketing communication strategies. The project was to experience many challenges ahead. However, already in the early phases of the project, participants agreed that this was a new type of project that had to be *managed in a very different way* than the average front-end. Out of curiosity, I tried to decode the root causes of the problems they experienced. I failed. The product developers seemed unable to precisely explain many of their problems, except from explaining that "*working with software and software people was something completely different*". This did not lend many clues to how to manage this type of project. This motivated me to formulate the thesis underlying the present study:

Projects developing products with both digital and physical components require different management approaches.

The project required different management approaches as it had to be hand-carried through the many functions and processes of the company until the product was eventually discontinued from the market. If disregarding the turbulent and unpredictable development, launch, and live phase operations, the product was overall successful in the market and won an award. However, it left a group of exhausted people behind who did not have a clear idea about how to successfully develop the next digital-physical product.

Digital-physical products are not a new phenomenon. As described in Hendler and Boer (2019), the first commercially available computer with software emerged in the 1950s (Kubie, 1994) and many products with embedded software followed, such as Kodak's digital camera from 1975 and music CD players from 1982. The continued rapid miniaturisation of computers and hardware, combined with their ever improving interface mechanisms, increasing processing power, storage capacity, communication bandwidth and more effective power management (Yoo et al., 2010) has enabled an increasing and pervasive digitalisation of non-digital products (Yoo et al., 2012). Products are becoming intelligent, self-adaptable with sensor feedback, remotely accessible, data-logging, communicating and nodes within Internets of Things. These features enable optimisation of product performance and extended value propositions. Digitalised products are booming within industries such as manufacturing machinery, furniture, buildings, vehicles, toys, shoes and clothing. Examples include Adidas

AG's Smart Ball and mobile app that measures the ball's speed, bend, spin and flight path, Happiest Baby Inc.'s smart baby crib and mobile app that responds to a baby with appropriate sound and motion to soothe the baby back to sleep, Samsonite International S.A.'s internet connected luggage line, Danfoss A/S's smart thermostats to precisely control the heating in your house, Michelin's smart truck tires that measure wear, Sega Toys Co., Ltd.'s iDog that lights up and dances to music, and Sensoria Inc.'s smart socks that inform you about your foot-landing technique.

For established manufacturers[1] with little or no software experience in their product development, such product digitalisation affects the entire value chain (Porter and Heppelmann, 2015). As an example, Volvo experienced "*shifts in the company's capabilities, routines, and structures in fundamental ways that would affect Volvo Cars' identity and culture*" (Svahn et al., 2017, p. 15). This includes the product development process in which the two different disciplines of software development and physical product development must be combined when interdependent development is required by the product concept.

Since the 1990s, software development has rapidly moved away from the plan-driven development processes known from physical product development (Rigby et al., 2016), such as Cooper's (1990) stage-gate model. Software development has become agile with short, iterative and incremental build-test-learn cycles (Rigby et al., 2016). It is optimised to adapt to high degrees of complexity and uncertainty in product requirements and solutions (Hendler, 2019). These agile methods enable fast learning and the ability to adapt accordingly (Cohn, 2010). Because of the digital immateriality, manufacturing is not required and fixed costs are limited (Hendler, 2019). Also, the immateriality means that there is no cost related to the number of products produced (Svahn and Henfridsson, 2012), no time spent on transportation (Hendler, 2019) and no scarce physical assets to consider, such as shelf space and manufacturing equipment (Könnölä, 2016; Eklund and Berger, 2017). Immaterial outputs are typically reprogrammable and are available after each small development increment in an incremental development process. The first increment is available very early after development initiation, which allows early feedback from customers to ensure that the product is relevant (Yoo et al., 2010). Finally, immateriality enables late commitment of many product features (late binding) as no manipulation of tangible materials is needed that requires long lead-times (Svahn and Henfridsson, 2012).

Physical product development is optimised for stable exploitation of investments and matured capabilities embedded in manufacturing equipment and refined process technology (Hendler, 2019). This encourages that product development is done incrementally and that platforms are developed to enable reuse (Svahn and

[1] I use the term manufacturer for a company that manufactures and, here, also develops physical products, in-house, as a core competence.

Henfridsson, 2012). Development, manufacturing and sourcing lead-times are relatively long and uncertainty is reduced with extensive front-end preparation and early binding of the product design (Svahn and Henfridsson, 2012).

Hence, not only does software development represent a product immateriality to the manufacturer requiring for example, different business models, maintenance strategies, distribution channels and return policies, but it also represents a different development method. Accordingly, Svahn and Henfridsson (2012, p. 3353) conclude that product manufacturers that are digitalising their products: "*... need to accommodate two innovation regimes in the same innovation process*". Svahn et al., (2015, p. 4124) add: "[incumbent firms] *need to develop entirely new sets of capabilities to resolve contradictions between digital innovation and product innovation*". Unfortunately, as established later in this thesis, practitioners cannot find much guidance from a scattered and immature field of literature (Svahn and Henfridsson, 2012; Nambisan et al., 2017; Holmström, 2018) with respect to how to effectively accommodate digital-physical product development[2]. Hence, the overall research objective guiding the research presented in this thesis is:

To explore how to effectively develop digital-physical products.

Thus, this research explores the process that results in a digital-physical product, i.e. the digital-physical product development process. *Effectively* refers to the extent to which goals are achieved, here, the performance goals of the digital-physical product development process. Product development performance is here understood in terms of indicators such as degree of success, survival, product competitiveness, development productivity, development lead time (Kuwashima and Fujimoto, 2013), and total product quality (Clark and Fujimoto, 1991). The research predominantly focuses on the product development phase that follows the front-end development phase and ends with a product launch. This phase presents significant differences between digital and physical development practices.

The research objective is posed by a practitioner and the study at hand is first and foremost aimed at helping practitioners by addressing a relevant topic in need of theory development. Answering Yoo et al.'s (2009) call for papers, this research will add to management theory (e.g. Nambisan et al., 2017; Holmström, 2018), specifically to the new field of digital-physical product development, by contributing with descriptive and tentative theory intended to develop statements of associations summarised in a model (Christensen, 2006) accompanied by propositions.

The research includes a literature review, and studies five digital-physical product development projects using case study and action research methods, all performed

[2] I use the term "digital-physical" to refer to the product and not the process. Physical refers to a tangible product without software and digital to software (Hendler, 2020).

within the same case company. This company is presented below. Subsequently, this chapter includes a presentation of the research objectives and questions of three peer-reviewed research papers that report the findings from the five projects. Then the theoretical background for the research is summarised and the high level research method selection is explained. Finally, the chapter describes the full structure of the present thesis.

1.2. EMPIRICAL BACKGROUND

The case company is a successful global manufacturer of a wide portfolio of B2C products for recreational and educational purpose. It has won several awards for its products. The company is henceforth labelled COMP, as it operates in highly competitive markets and therefore wishes to remain anonymous to protect product and operational information. COMP employs more than 16,000 people across multiple manufacturing sites worldwide and one main product development site. It holds an "*elaborate and mature core product development process*", which "*includes more than*" 200 "*milestones across a front-end and a subsequent execution phase*" (Hendler (2019), Appendix B, p. 199). The front-end process is characterised by relatively high uncertainty, which, at the hand-over to the execution phase is significantly reduced to a low risk business case and concept prototype.

The execution phase is characterised by relatively low uncertainty and deploys a plan-driven development method "*following elaborate process standards*" with "*early planning of detailed deliverables up to one year ahead*" (Hendler (2020), Appendix C, p. 239). That phase includes multiple subprocesses resulting in a physical product, go-to-market strategies, marketing material, packaging and instruction manuals. The development process is executed by a project team of at least 30 members. Depending on the size of the project, many project members contribute to multiple projects at a time. The members adhere to matured and standardised development, support and manufacturing processes, which are dependent on highly specialised skills. Efficient development of product components is enabled by mature product platforms and relatively stable markets. Functional departments develop the product components following department-specific subprocesses and influenced by their own priorities (Hendler, 2020). The highly stable execution phase locks its Bill of Materials[3] early to enable an efficient and predictable lean planning and manufacturing process. The development process is focused on delivering high levels of cost-effective product quality without delays. For more than a decade, and helped by a stable market, no product launch has been late in COMP.

[3] Bill of Materials refer to a list of the raw materials, parts, components and the quantities of each needed to manufacture a physical product. The list is used by R&D to communicate to a manufacturing facility.

Figure 1 depicts the most important milestones, i.e. the highest cost of delay[4] milestones, from the perspective of COMP's product development.

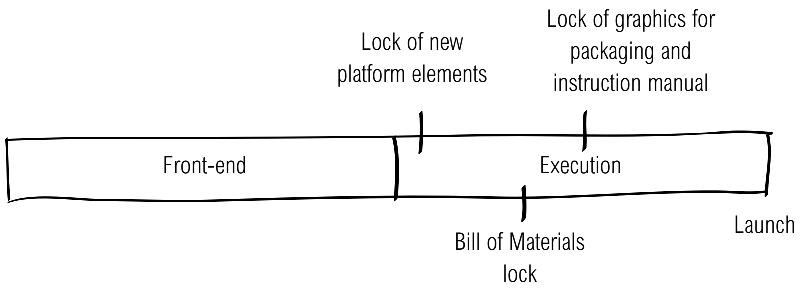

Figure 1 Key milestones in COMP's product development process

With recent market changes and the fear of becoming irrelevant to a potentially large market segment, COMP has decided to begin digitalising a small percentage of its portfolio. The challenge for COMP is to develop the capability to stably, efficiently and effectively deliver digital-physical products to a large or global market. Within this context, the study collects data from five of COMP's first digital-physical product development projects. Project A was the first digital-physical project to respond to the new strategy. Projects B and C followed, benefitting from the learning from Project A. Finally, projects D and E were able to develop digital-physical products with more mature management and development practices (see Figure 2). All five projects were profitable.

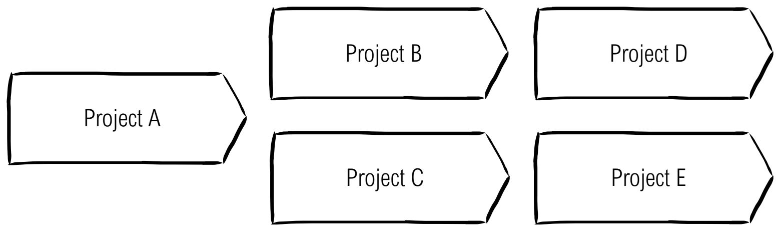

Figure 2 Sequence of the projects in COMP

Projects A-E involved a lot of "*collaboration with world-class external software partners*" who used "*state-of-the-art technology and agile development practices*"

[4] The cost of delay refers to the cost of delaying the launch of a product, a milestone or an activity and is measured in cost per time increment (Reinertsen, 2009).

(Hendler (2019), Appendix B, p. 199). The partners were involved with digital development after the physical front-end phase and until end of product life. COMP's digital-physical product development projects included up to double the number of project members in comparison with purely physical projects. In projects A, B, D and E, COMP led the combined product development project, whereas the digital partner led part of the development in Project C.

Below, the resulting digital-physical products from the five projects are briefly characterised, while disguising them. To increase the relatability of the research, an example is provided for each project, which describes a product that requires the same level of digital-physical process interdependency during its development as was the case in the COMP products.

1.2.1. PROJECT A

This product includes a physical product and an app for a third party mobile device like a smartphone or tablet. The user needs both components to harness the intended product value. The digital and the physical components are integrated in use as part of the user journey. A similar digital-physical integration example could be an animation app sold together with a physical doll's house. The user would then film or photograph scenes from the doll's house. Elements from these scenes would be recognised by the software, to make video stories about life in the doll's house.

1.2.2. PROJECT B

This product includes software for a third party device, firmware, hardware[5] and a physical product. Like project A, the physical product is replicated digitally and it is enhanced in the digital space with various digital functionalities. An example could be Activision's Skylanders. A video game that scans physical toy characters into the game via a physical device to become digital playable characters.

1.2.3. PROJECT C

This product includes a physical component and a mobile device app. The digital and the physical components can be used separately, or the physical products can be used to inform the software. No hardware or firmware was developed. An example of such digital-physical integration could be a product consisting of music making software and a musical instrument. The software can record the sound from the instrument to

[5] "Hardware refers to the electronics with the required input and output components, such as sensors and actuators, needed to" digitalise "the otherwise non-digital product" (Hendler (2020), Appendix C, p. 234).

enrich the sound options in the digital space for creative outlet and to easily be able to share recordings with friends.

1.2.4. PROJECT D

As described in Hendler (2020), the product consists of a physical product and software in the form of a mobile device app. No hardware or firmware was developed and the digital and physical components are integrated in use through a mobile device (Hendler, 2020). "*The physical product is used together with the information provided by* [an] *app in which the physical product is mirrored and modified*. *An example of a product with a similar digital-physical integration could be a high-end comic book that allows you to scan individual pages with a mobile phone, which in return adds sound effects while you read the individual pages and mirrors the pages to add new characters in them that an author had originally intended"* (Hendler (2020), Appendix C, p. 234).

1.2.5. PROJECT E

This product includes both "*internally developed hardware, software and firmware*" as well as "*externally developed software in the form of an app*" (Hendler (2020), Appendix C, p. 235). The developed digital and physical components are integrated in use via a mobile device app and via the physical product with electronics, firmware, sensors and actuators. "*An example of a product with a similar digital-physical integration could be a baby cot that can soothe the baby through various rocking patterns and sounds via actuators, speakers, microphones and a smartphone*" (Hendler (2020), Appendix C, p. 235).

Table 1 Overview of the digital and physical product components across projects A-E in COMP.

Projects	A	B	C	D	E
Internally developed physical product	x	x	x	x	x
Externally developed software	x	x	x	x	x
Internally developed software					x
Internally developed firmware					x
Externally developed firmware		x			
Externally developed hardware		x			
Internally developed hardware					x
3rd party devices	x	x	x	x	x

Table 1 gives an overview of the digital-physical product components across the five projects.

Using the terminology from Table 1, digital development produces software and firmware. Physical product development produces a physical product, sometimes including hardware, available in the market, packaged with an instruction manual and supported by marketing materials.

1.3. RESEARCH PAPERS, QUESTIONS AND OBJECTIVES

This thesis summarises, discusses and adds to three published journal papers that all contribute with descriptive theory on how to effectively develop digital-physical products. The three research papers are available in Appendix A, B and C. Below the question and objectives guiding the research papers are presented.

1.3.1. HENDLER AND BOER, 2019

The first paper is titled "*Digital-physical product development: A review and research agenda*" (Hendler and Boer (2019), Appendix A). It reviews existing literature on digital-physical product development.

Existing literature on digital-physical product development is scattered and immature (Svahn and Henfridsson, 2012; Nambisan et al., 2017; Holmström, 2018). Hendler and Boer (2019) show that literature on relevant fields such as embedded software development, systems engineering and development of smart and hybrid products, product-service systems, cyber-physical systems and complex products (e.g., Baines et al., 2007; Wolfenstetter et al., 2016; Bialasiewicz, 2017; Maleki et al., 2017) do describe some relevant practices, but often focus on more technical aspects (Haghighatkhah et al., 2017) or fail to problematise the combination of two different development methods and materialities, i.e. digital and physical. Furthermore, given differences when comparing software and manufacturing companies, such as how they organise and how they design their HR policies, the context within a company that can effectively support digital-physical development is unclear (Porter and Heppelmann, 2015). Thus, Hendler and Boer (2019, Appendix A, p. 163) is guided by the question:

"Which development practices and context effectively support the digital-physical development process?"

1.3.2. HENDLER, 2019

The second paper "*Digital-physical product development: A qualitative analysis*" (Hendler (2019), Appendix B) uses data collected from projects A, B and C, and explores not only the development practices and their context but also the practices used to coordinate the concurrent digital and physical product development processes. Addressing the topic of how companies can effectively coordinate different cycle lengths with different information needs at different points in time as well as late vs. early binding of product design, the second paper is guided by the objective (Hendler, (2019), Appendix B, p. 194):

"To identify effective development, coordination and contextual practices supporting the combined digital-physical development process."

1.3.3. HENDLER, 2020

With the aim of providing relevant theory, the third paper "*Exploring coordination practices in digital-physical product development*" (Hendler (2020), Appendix C) explores and tests a number of specific coordination practices within projects D and E. The focus is to test practices that can effectively combine the digital and the physical product development processes in order to optimise the performance of the combined digital-physical development project. The research objective is (Hendler, (2020), Appendix C, p. 225):

"To explore coordination practices in digital-physical development and their consequences for companies traditionally relying on physical development."

The contributions from the three journal papers are summarised and discussed in Chapter 2.

1.4. THEORETICAL BACKGROUND

Though emerging, scattered and immature, the theoretical background provides an important starting point underpinning the literature-based contribution of Hendler and Boer (2019) as well as supporting Hendler (2019) and inspiring the coordination practices developed and tested in Hendler (2020). The emerging field of digital-physical literature is summarised below. The analysis shows that the literature is predominantly based on anecdotal accounts from case study descriptions, which do not always problematise digital-physical product development, but still provide relevant descriptions of the phenomenon. See Hendler and Boer (2019) for more details. With hardly any theory available describing digital-physical product development, this theoretical background therefore includes adjacent fields of theory on innovation management, organisation design, as well as popular practices from agile software development. Thus, this background provides a lens of constructs, such as various agile and coordination practices, to help the development of tentative theory on how to effectively develop digital-physical products.

This background first describes the differences between digital and physical development practices as they are observed, predominantly, in case studies that combine the two. This first description is based on the literature study presented in Hendler and Boer (2019). To help explore the thesis objective that is concerned with how digital and physical product development can be combined into one development effort, the focus is on the differences that emerge when digital and physical product development are combined, and not on accounting for all the differences between the two sets of practices. Second, the practices used to combine the two processes are described. Third, the combined digital-physical process is described in terms of its managerial challenges as well as suggestions for suitable development practices. Then, the context suitable to support digital-physical product development is summarised. The descriptions of the combined digital-physical process and the suitable context are both based on Hendler and Boer (2019). Finally, to help explore the theme of this study, theory from innovation management as well as coordination theory from organisation design and established practices from agile development methods are summarised. See Hendler (2020) for more details.

1.4.1. DIFFERENT DEVELOPMENT PRACTICES

The literature predominantly describes digital-physical product development as a process in which the physical and the digital development activities largely take place in separate teams and follow different development methods in separate, albeit concurrent, development subprocesses (Joglekar and Rosenthal, 2003; Broy, 2005; Broy et al., 2007; Woodward and Mosterman, 2007; Cordeiro et al., 2008; Huang et al., 2012b; Katumba and Knauss, 2014; Lerch and Gotsch, 2015; Lwakatare et al., 2016). When coordinating the digital and physical product development subprocesses several differences become evident as summarised in Table 2 below (Hendler and Boer, 2019).

Due to more stable technologies and markets, physical product development typically deploys detailed and plan-driven development methods from idea to launch (Svahn, 2012; Svahn and Henfridsson, 2012), such as Cooper’s popular stage-gate model (Cooper, 2016). Much attention is paid to risk reduction via deviation management and early binding of the product specification is practiced to secure that the product scope remains fixed (Svahn and Henfridsson, 2012; Cooper, 2016; Eklund and Berger, 2017) to enable stable manufacturing processes that can achieve predictable efficiencies and economy of scale. The product development efforts are coordinated by one overarching, long and linear development cycle, taking up to several years with relatively limited customer involvement and prototyping loops of several months’ duration (e.g. Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund et al., 2014; Lwakatare et al., 2016).

Table 2 Dissimilar development practices (Source: Hendler and Boer, 2019)

Physical product development	Digital product development
• One long development cycle (years) with few prototype iterations (months) typically governed by a linear staged and gated model	• Many short iteration cycles (weeks) using agile development methods with frequent releases
• Early binding: Extensive up front planning with early specification lock assuming long term predictability	• Late binding: Evolvement of requirements throughout development assuming poor long term predictability
• Detailed information needed later in the process	• Detailed information needed already early in the development
• Limited user involvement	• Extensive user involvement
• Product development project stops after launch	• Product development continues after initial launch until end of product life
• Focus on minimizing variation via planning and deviation management	• Focus on exploiting variation via frequent transparency based decision-making and flexible scope
• Key process performance measures: time to market; reduction in inventory costs; manufacturability	• Key process performance measures: development costs
• Optimise for exploitation, stability and some flexibility	• Optimise for exploration and agility
• Tools, language and norms adapted to physical product development	• Tools, language and norms adapted to digital product development
• Budget and time are flexible	• Scope is flexible
• Firm-centric development	• External orientation with distributed development
• Medium need for process structure and clear completion points	• High need for process structure and clear completion points
• High marginal and fixed costs	• No marginal and limited fixed costs
• Soft factors contribute less to project success	• Soft factors contribute greatly to project success
• Development is predominantly organised in component teams without end-to-end visibility of the value stream	• Development is predominantly organised in cross-functional feature teams

Agile software development, in contrast, accommodates complex development efforts and uncertainty in the product scope caused by fast-moving markets with infinite possibilities. Therefore, customer requirements are being discovered over time in multiple development cycles of, typically, two to four weeks and with extensive involvement of the customer or a customer representative (Karlström and Runeson, 2006; Svahn and Henfridsson, 2012; Eklund and Bosch, 2012; Eklund et al., 2014; Lwakatare et al., 2016; Mocker and Fonstad, 2018). The product scope is adaptable. However, the budget and the schedule are fixed (Cooper, 2016). The immaterial software also means that it can be changed after product launch and there is no need for long lead times for the manufacturing of prototypes or tooling for the manufacturing, for example (Schwaber and Beedle, 2001; Cohn, 2010; Yoo, 2010; Könnölä et al., 2016; Eklund and Berger, 2017). As a result, the costs of product iterations are higher for physical compared to software development. Physical development also focuses on unit cost reduction, a marginal cost, which is irrelevant to software, whose primary cost is the development hours, a fixed cost (Joglekar and Rosenthal, 2003; Broy et al., 2007; Svahn, 2012). Thus, for software development a key process performance measure is the development costs, whereas physical development considers time to market, reduction in inventory costs and manufacturability (Joglekar and Rosenthal, 2003)

The different development methods imply differences in project organisation, roles, tools and planning (Karlström and Runeson, 2006) as well as differences in norms and language (Karlsson and Lovén, 2005; Lee and Berente, 2012; Eklund et al., 2014; Porter and Heppelmann, 2015; Cooper, 2016; Mocker and Fonstad, 2018). Traditionally, physical product development represents a firm-centric view, whereas digital development is more likely to see innovation as a boundary-spanning activity requiring a distributed effort (Svahn and Henfridsson, 2012). Furthermore, Hendler and Boer (2019, Appendix A, p. 172) describe that "*physical product development is predominantly organised into functionally specialised component teams*" based on modular architectures (Andreasson and Henfridsson, 2008; Svahn et al., 2009), and digital development in cross-functional teams to deliver a fully functional product (Lwakatare et al., 2016; Könnölä et al., 2016; Mocker and Fonstad, 2018). Due to a need for more cross-functional collaboration and a high complexity, soft factors greatly contribute to digital development success (Kettunen, 2003).

In summary, the literature describes two different development practices. Software development is designed to discover the product scope, increment by increment, through fast learning cycles in cross-functional teams due to high levels of complexity and uncertainty. Relative to the *adaptability*-optimised software development, physical development seeks to *stabilise* the product scope in the process through early binding to optimise for a low unit cost via stable processes, technologies and manufacturing. Considering a continuum from stability-optimised to adaptability-optimised processes, software development is placed much closer to the 'adaptability-optimised' end of the continuum, relative to physical product development. To better understand the innovation management challenge involved in combining digital and physical product development, Svahn and Henfridsson (2012, p. 3354) conclude "*it would be useful to understand the dynamics that emerge from their interaction"*. Hence, with little relevant literature available, exploring how to effectively develop digital-physical products involves understanding the consequences of their combination and how to effectively combine two different development methods.

1.4.2. COMBINATION PRACTICES AND THEIR PERFORMANCE IMPACT

The digital and physical development subprocesses typically need to coordinate their efforts to be able to discover, deliver and, possibly, operate a live digital-physical product. The dominant overall coordination practice observed by the literature is, according to Hendler and Boer (2019, Appendix A, p. 173) the "*long-term, plan-driven staged and gated approach that is used by physical product development*" (e.g. Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund and Bosch, 2012; Eklund et al., 2014; Lwakatare et al., 2016). Only a few case studies report how both the digital and the physical subprocess have been orchestrated by an agile development method (Huang et al., 2012a, b; Könnölä et al., 2016; Eklund and Berger, 2017). Cooper (2016) reports on digital-physical development being done with an agile-stage-gate model. The results of these different approaches are mixed and the differences between digital and physical development subprocesses complicate effective coordination.

First, a number of challenges have been reported when using the plan-driven, staged and gated approaches as the dominant coordination practice. Many of these challenges are related to the digital development methods being compromised by adapting to the coordination practices that fit the physical product development, with consequences for development performance (e.g. Diegel et al., 2008; Evans, 2009; Eklund and Bosch, 2012). Specifically, an early and long planning phase, as well as early binding and rigid gates, are observed to be imposed upon the digital development process(es), which challenge the agile practices designed for late binding, incremental planning, and fast change. The staged and gated model does not seem to be able to accommodate enough adaptability for software development (Karlström and Runeson, 2006; Eklund and Berger, 2017). Hendler and Boer (2019) summarise other challenges which involve differences in information needs at different points in time (Karlström and Runeson, 2006), the risk of releasing 'old software' due to the long physical development cycle (Eklund and Bosch, 2012), obliging software developers to prepare the required low-uncertainty gate-required documentation, and adapting to established governance structures and role expectations (e.g. Joglekar and Rosenthal, 2003; Karlström and Runeson, 2006; Rottier and Rodrigues, 2008; Eklund and Bosch, 2012; Cooper, 2016). In some reported cases, it is only when the mechanical product concept is locked that software development starts (Hendler and Boer, 2019). This, however, results in concepts of questionable digital quality and the risk to underutilise possibilities enabled by digital technologies (Karlström and Runeson, 2006; Yuan et al., 2008; Diegel et al., 2008; Evans, 2009; Eklund et al., 2014).

Second, several challenges have also been observed when using agile methods for coordinating the digital and physical subprocesses. These include finding good coordination frequencies to cope with different development cycle times, designing good team constellations (Könnölä et al., 2016; Eklund and Berger, 2017) and managing the flow of tasks in teams when multiple tasks can only sit with specific functional roles (Könnölä et al., 2016). Similar to digital development adapting to the physical process to solve coordination problems, the literature also suggests how physical can adapt to solve coordination problems when agile methods are coordinating the processes. However, these suggestion have not been implemented in the case studies reported in the literature. Some suggestions involve designing fully cross-functional teams across digital and physical competences (Könnölä et al., 2016; Eklund and Berger, 2017), accepting that requirements will be uncovered and locked gradually (Karlström and Runeson, 2006; Eklund and Bosch, 2012), developing physical products based on platforms to shorten the duration of the development increments, working to reduce the number of interdependencies between digital and physical development, and allowing incomplete components for digital-physical prototyping (Eklund and Berger, 2017). Finally, Könnölä et al. (2016) suggests to involve the surrounding company context in agile practices to gain wider system benefits.

In addition to the many challenges, the literature also observes a few benefits when coordinating digital and physical development processes which are summarised in Hendler and Boer (2019). Huang et al. (2012a, b) and Cooper (2016) observe that agile practices have been used successfully for the development of digital-physical products. However, Cooper (2016) only describes the cases from a high level perspective and does not problematise the combination of different development disciplines. Karlström and Runeson (2006) observe that merging the detailed planning practices seen within agile with the planning of end-to-end roadmaps carried out as part of the staged and gated development methods has positive outcomes. Yet other authors observe how errors and risks that arise in the physical product development process can be mitigated using agile development methods in the software development process (Rauscher and Smith, 1995; Joglekar and Rosenthal, 2003; Greene, 2004; Rottier and Rodrigues, 2008) by e.g. adding mitigating digital features late in the development process. Hendler and Boer (2019) also describe how some authors suggest that if an agile framework is used for digital-physical coordination, the agile practices will allow the development of the physical product to adapt to, more readily, any new information about, for instance, customer preferences and technical challenges (Huang et al., 2012b) and enable software design decisions to drive the physical product design decisions while hardware components increasingly become commodities (Evans, 2009). A few authors propose benefits of keeping the digital and physical development processes separate (Dagnino, 2001; Yuan et al., 2008; Evans, 2009), e.g. by avoiding interdependencies in the development process via well-designed digital-physical product architectures (Yoo et al., 2010) with clear digital-physical interfaces.

In summary, the majority of cases describes a combination of digital and physical development processes via staged and gated overall process models with software development adapting to physical development to overcome many of the coordination challenges. This adaptation has detrimental performance effects, though. The literature does not present theory on digital-physical coordination practices, nor the right level of digital-physical process integration or which of the processes, if any, should adapt to the other in order to achieve the best overall digital-physical product development performance.

1.4.3. THE COMBINED PROCESS

The combined process of digital-physical product development presents a long list of new challenges to the manufacturer (Hendler and Boer, 2019). The multifaceted process involves more complex trade-off decisions and specifications, more errors (e.g. Durrett et al., 2002; Karlsson and Lovén, 2005; Rottman, 2006; Woodward and Mosterman, 2007; Yuan et al., 2008; Katumba and Knauss, 2014), increased cross-functionality, more partnerships with new external actors from new industries (Dawid et al., 2017), and requires the orchestration of many new interdependencies (Eklund and Berger, 2017). The digital-physical development process now includes both material and immaterial product components of which only the immaterial ones can be re-programmed. Hendler and Boer (2019) condense that new practices are needed such as designing for improvements and maintenance after launch (e.g. Broy, 2005; Porter and Heppelmann, 2015; Eklund and Berger, 2017), and considering big data and security design features (Porter and Heppelmann, 2015).

Digital-physical product development also involves a layered product architecture with loose couplings (Yoo et al., 2010), which Hendler and Boer (2019) consolidate may require new practices including horizontal innovation and combinatorial innovation (Yoo et al., 2012), designing digital generic building blocks that can be utilised, combined and built upon for future innovation challenges (Svahn et al., 2017), product variations and coupling with complementary products (Svahn et al., 2015), system interoperability (Porter and Heppelmann, 2015) and distributed innovation (Yoo et al., 2010). Digital-physical product development also requires the manufacturer to adopt new methods for market analysis (Dawid et al., 2017), extracting tacit user knowledge (Abrell et al., 2016) and engaging with a new type of suppliers, which requires procurement to develop new contracts enabling sustainable relationships and co-creation (Svahn et al., 2017). Overall, however, the literature, portrays a scattered picture of challenges, suggests some suitable development practices, but does not propose actionable theory.

To conclude, the combined process of digital-physical product development likely involves the manufacturer to consider a number of new practices across the value chain, such as designing for big data, system interoperability and combinatorial innovation. However, with a lack of actionable theory, more research is needed to explore such suitable practices.

1.4.4. THE DIFFERENT CONTEXTS

Hendler and Boer (2019) consolidate that when a manufacturer digitalises its products, it enters a new industry structure including new competitors, expanding boundaries, extensive product systems, increased technological pressures, and new strategic opportunities (Svahn and Henfridsson, 2012; Porter and Heppelmann, 2014; Yoo et al., 2010, 2012). Therefore, not only the development process must adapt, but the literature also observes a need to significantly adapt the development context within the manufacturer in order for the company to be able to effectively support the development activities (Andreasson and Henfridsson, 2008; Svahn and Henfridsson, 2012; Porter and Heppelmann, 2014; Yoo et al., 2010; Yoo et al., 2012, Svahn et al., 2015) while ideally continuing the exploitation of many stability-optimised practices for the purely physical part of its product portfolio. Examples of new adaptations needed include topics such as strategy (Porter and Heppelmann, 2015; Yoo et al., 2010; Yoo et al., 2012; Dawid et al., 2017), organisational structure (Joglekar and Rosenthal, 2003; Broy et al., 2007; Katumba and Knauss, 2014; Porter and Heppelmann, 2015), culture (Kettunen, 2003; Karlsson and Lovén, 2005; Porter and Heppelmann, 2015) functional skills and tools (Broy, 2005; Broy et al., 2007; Yoo et al., 2010; Porter and Heppelmann, 2015; Dawid et al., 2017). New capabilities may include the offering of broader product systems, new servitisation strategies, big data management (Porter and Heppelmann, 2015), and post-launch software operations processes (Broy, 2005; Broy et al., 2007; Porter and Heppelmann, 2015). Porter and Heppelmann (2015) argue that in the case of smart connected products there is a need to add three new areas to the manufacturer's organisation: 1) a unified data organisation, 2) a development-operations group (or dev-ops), and 3) a customer success management unit. Additionally, they argue for an increased need for multiple new lateral linkages between various departments. Furthermore, Dawid et al. (2017) explain how more flexible or agile supply chains may need to co-exist with a more stable and lean-optimised value chain for the existing portfolio. Finally, Karlström and Runeson (2006) mention issues such as traditional management not feeling at ease with the agile development methods used in software, and Porter and Heppelmann (2015) suggest that the human resources organisations will have to reconsider how the organisation is structured, as well as norms and policies to effectively combine the two different development working styles.

In summary, the manufacturer must rethink both the way it does product development in terms of its processes, as well as the development context supporting it (Hendler and Boer, 2019). Proposed topics include skill requirements, organisational structure, and culture, capabilities, strategy, and HR policies. More research is needed to explore these proposed changes.

1.4.5. SUITABLE PROCESS MANAGEMENT

Boer and During (2001, p. 86) propose that the success of an innovation process depends on "*the extent to which the manager is able to fit the organization of the process to the demands created by* [its] *characteristics*". These characteristics are uncertainty, diversity, complexity and interdependency. Boer and During (2001) define uncertainty as "*the extent to which individuals, groups or organisations are informed about the future*" (p. 86). Diversity denotes "*the variety of the work that needs to be done, in terms of the number of competences needed to perform the innovation process*" (p. 86). Complexity refers to "*the difficulty with which the work can be understood*" (p.86). Interdependence is "*the extent to which (groups of) people depend on each other for their functioning*" (p.86).

The organisation of an innovation process needs to fit these characteristics (Boer and During, 2001). In Hendler (2019) and Hendler (2020), this suggestion is used to describe and analyse the digital-physical development process, its digital and physical subprocesses, their similarities and differences, and implications for the management of the digital-physical development process.

1.4.6. COORDINATION THEORY

Due to a lack of specific theory on digital-physical coordination, theory from adjacent areas of literature is used to develop new theory on how to coordinate digital and physical product development. In this study, the primary coordination theory used for this purpose is Mintzberg's (1979) continuum of coordination mechanisms from organisation theory, as well as three popular agile frameworks that include various coordination practices. The descriptions below are taking a starting point in Hendler (2020).

Mintzberg's continuum

Mintzberg's (1979) continuum of coordination mechanisms ranges from mutual adjustment, through direct supervision and standardisation of work, output or skills, back to mutual adjustment (see Figure 3).

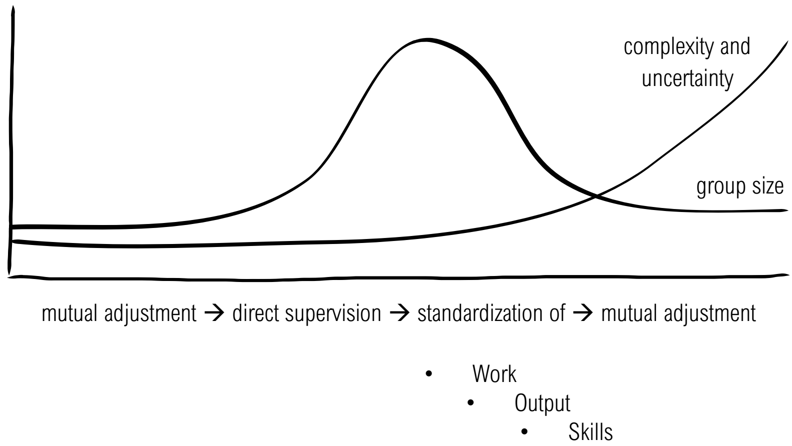

Figure 3 A contingent continuum of coordination mechanisms (Source: Hendler (2020), inspired by Mintzberg, 1979)

Which mechanism is most suitable depends on a number of characteristics: the complexity and uncertainty, or analysability and variety of the tasks to be performed (Perrow, 1967) and the size of a group performing them. The mechanisms are explicated below.

- Mutual adjustment: This mechanism refers to the coordination of the tasks performed by a small group whose tasks can be characterised as either predictable, simple, analysable and low-variety, or as having high complexity, uncertainty, being non-analysable and highly variable.
- Direct supervision: This mechanism refers to the leader of a larger group who is directly coordinating the tasks performed by the group. These tasks are predictable, simple, analysable, and have a low level of variety.
- Standardisation of:
  - Work: Applies to a large group performing a still relatively simple, predictable, analysable, low variety (i.e. routine) task.
  - Output: Applies to a smaller group performing a more complex, less predictable, less analysable, and higher variety task.
  - Skills: Applies to a yet smaller group conducting tasks that are even less predictable, more complex, less analysable, and higher variety.

Agile process frameworks

Agile development practices are aimed at facilitating effective team learning as part of highly complex and uncertain software development processes. Therefore, these agile methods include a large number of highly effective coordination practices for complex and uncertain processes. The practices are built upon the agile manifesto of principles and values (Beck et al., 2001), such as "*Welcome changing requirements,* *even late in development*", "*Build projects around motivated individuals. Give them the environment and support they need, and trust them to get the job done*" and "*The most efficient and effective method of conveying information to and within a development team is face-to-face conversation*". Hence, the agile coordination practices facilitate frequent, decentralised decision-making. Widely used coordination frameworks include Large Scale Scrum (LeSS) (Larman and Vodde, 2016), scrum (Sutherland, 2015), and Scaled Agile Framework (SAFe) (Knaster and Leffingwell, 2017). Examples of practices included in these frameworks are planning of program increments, i.e. planning that spans several sprints and teams every twelve weeks, team planning meetings in the beginning of each sprint, typically every two to four weeks, in which also the sprint's goal is set, daily stand-up meetings focused around a kanban or a scrum board, and sprint output reviews and retrospective meetings. All these practices evolve around cross-functionality, visual planning tools, empowerment and transparency.

A key purpose of this extensive and formalised set of coordination practices of a mostly horizontal nature is to enable fast changes to new information (Bernardes and Hanna, 2009) by utilising a stable and proven process framework (Sutherland, 2015). Hence, the desired *adaptability* with respect to product features is achieved through highly *stable* processes, values, principles, and teams.

In summary, Mintzberg's (1979) continuum and instantiations such as Scaled Agile Framework (SAFe) (Knaster and Leffingwell, 2017), Large Scale Scrum (LeSS) (Larman and Vodde, 2016) and scrum (Sutherland, 2015) include various coordination mechanisms and specific coordination practices. The coordination mechanisms range from direct supervision and standardisation of work, output and skill which are effective for tasks with low complexity and uncertainty, to mutual adjustment facilitated by agile sprint planning meetings and stand-ups that are effective for highly uncertain and complex tasks. With no available theory and with digital-physical product development encompassing two different sets of development practices, further exploration is needed to determine what set of coordination mechanisms and practices work best when, how and why.

1.4.7. SUMMARY AND CONCLUSIONS

This theoretical background summarises an emerging, scattered and immature body of literature as well as selected adjacent fields of literature. It provides the basis for the further research that is presented in this PhD thesis into digital-physical product development and how to combine the two sets of practices by providing a lens of constructs, such as various coordination practices and process characteristics, to help the development of tentative theory on how to effectively develop digital-physical products, i.e. how to combine digital and physical product development into one development effort. See Hendler and Boer (2019) for an elaboration of the theoretical background of digital-physical product development.

First, the literature describes two different sets of development practices. Digital development is aimed at discovering and *adapting* the product scope through fast learning cycles in cross-functional teams. Relative to digital development, physical product development is aimed at *stabilizing* the product scope early in the process to optimise for a low unit cost. The literature does not provide mature theory into the dynamics that emerge from the interaction between the two sets of practices in digital-physical product development, and, instead, calls for the need for further research. Furthermore, the majority of case studies account that digital and physical development processes are combined via staged and gated process models with software development adapting to physical development. This adaptation is done to overcome the coordination challenges that arise when combining the two dissimilar sets of practices. Unfortunately, theory on digital-physical coordination practices is not available. Neither is it clear if the best overall digital-physical product development performance is achieved by adapting digital development to physical, physical to digital, or maybe a third option. The literature also suggests a need for the manufacturer to develop new practices across its product development value chain, including the intra-company context supporting it. Therefore, with a lack of actionable theory, this thesis aims to contribute to closing this gap by exploring the needed changes, i.e. how to effectively develop digital-physical products.

To aide this exploration, the research presented in this thesis deploys theory from innovation management and organisation design, as well as popular practices from agile software development. First, Boer and During (2001) propose that the level of uncertainty, interdependency, complexity and diversity that characterises an innovation process require a certain management. This proposal is used as a lens of constructs to analyse and understand the management needed of the digital-physical product development process. The theory complements the thesis statement: "*Projects developing products with both digital and physical components require different management approaches".* Second, with no available coordination theory in the digital-physical product development literature, Mintzberg's (1979) continuum of coordination mechanisms from organisation design theory and the coordination practices embedded in three popular agile frameworks are also used as a lens of constructs to explore how to effectively combine digital and physical product development.

1.5. METHODOLOGY

Given an immature and scattered body of research that is in the beginning of descriptive theory building (see Hendler and Boer (2019) and Christensen (2006)), exploring *how* to effectively develop digital-physical products requires qualitative research that can provide new and empirically valid concepts and ideas for further expansion and testing (Eisenhardt, 1989; Gioia, 2012). Qualitative methods can explore new complex social phenomena, enhance data by searching for non-obvious features and multiple interpretations, and offer complex descriptions, explanations and operational guidelines (Have, 2004). Hence, with an exploratory and qualitative approach, the underlying logic behind the selection of the specific methods applied in this study is expressed in the following questions:

1. What can we learn about digital-physical product development from literature (literature review, Hendler and Boer (2019))?
2. What can we learn from empirical practice (case study, Hendler (2019) and Hendler (2020))?
3. How can we test and demonstrate the effectiveness of key practices for managers involved in digital-physical product development projects (action research, Hendler (2020))?

The methods and the reasoning behind their selection are described below.

1.5.1. LITERATURE REVIEW

To establish the relevance and explore the topic of this research, a systematic literature review helps developing answers to a number of questions (McNiff and Whitehead, 2011):

- What have other people said about this topic?
- What are potential constructs and relationships that are important when problematizing the topic and that further research needs to be sensitive to?
- What is the originality and significance of the contributions to knowledge of this study?
- What is the fit of the contributions to knowledge of this study against the research of other authors?

Hence, as described in Hendler and Boer (2019, Appendix A, p. 163), a "*literature review provides input for further research*" such as "*uncovering knowledge about the domain*" including "*constructs, relationships and explanations*" of insight (Whetten, 1989), in this case, into digital-physical product development. The details of the literature review performed for the purpose of this research, the method used and the clarified knowledge gaps from the perspective of a manager on digital-physical product development are provided in Hendler and Boer (2019).

1.5.2. CASE STUDY

In accordance with Yin (2009), the case study method is used in this study to explore a social phenomenon that is embedded in its context, which is both contemporary and complex. The case study method is relevant when answering the *how* question implied by the objective *to explore how to effectively develop digital-physical products*, and appropriate when control over the behavioural events is limited, i.e. the investigator cannot manipulate behaviour directly, precisely and systematically like in a laboratory

(Yin, 2009). Eisenhardt (1989, p. 548-549) concludes that the case study method "*is particularly well-suited to new research or research areas for which existing theory seems inadequate. This type of work is highly complementary to incremental theory building ... in early stages of research on a topic or when a fresh perspective is needed*".

Thus, contributing to such early-stage incremental theory building, the constructs and relationships suggested in the literature review are merely used to guide the subsequent case study and action research presented in this thesis. They are considered as tentative due to the immature and scattered body of literature and to encourage iteration between data and theory as part of the case study analysis as advised by Eisenhardt (1989) to facilitate empirically valid results. The case study method "*expands and generalizes theories*" (Yin, 2009, p. 15). Bassey prefers to use the term *relatability* over *generalizability*. He explains: "*an important criterion for judging the merit of a case study is the extent to which the details are sufficient and appropriate for a teacher working in a similar situation to relate his decision making to that described in the case study*" (Bassey, 1981, p. 85). Accordingly, the case studies performed in this study is sought to be described with sufficient detail to allow practitioners to relate to the theory and enable analytical generalisation (Yin, 2009). Finally, the researcher had an established relationship with the case company and knew of its need to solve problems related to digital-physical product development. Hence, the choice of the case company was a result of convenience sampling.

1.5.3. ACTION RESEARCH

Also action research is used as a data collection method. Action research is research concurrent with action and produces actionable theory (Coghlan and Brannick, 2010). It consists of problem solving loops that are also aimed at testing theory. The loops include three steps: 1) plan, 2) act and 3) fact-find (Lewin, 1946/1997). Hence, action research enables testing various practices in a rich complex environment while uncovering the most important mechanisms and trade-offs in a specific context. Consequently, action research results in rich and effective learning via fast feedback while solving a practical problem, in this case within COMP.

Action research diaries serve as the primary data documentation and are structured in accordance with Kolb's learning cycle as presented by Coghlan and Brannick (2010). See Hendler (2020) and Chapter 3 for how this method has been applied and Appendix D for the structure of the diary.

Combining these three methods, i.e. literature review, case study and action research, allows an in-depth exploration of COMP's digital-physical product development to contribute to the incremental development of tentative theory on digital-physical product development. The resulting tentative theory is essentially describing a specific phenomenon, i.e. what COMP understands as successful, or at least sufficing, digital-physical product development practices. Furthermore, this understanding is often determined based on subjective statements. It requires more research to determine if the practices that are considered successful in COMP also apply to other companies. External validity and the research limitations are discussed in Chapter 5.

1.6. THESIS STRUCTURE

Chapter 1 has introduced the thesis topic, journal papers, background and methods. Chapter 2 summarises and discusses the contributions of the three journal papers to clarify how to effectively develop digital-physical products. Furthermore, additional findings, core to the topic of the thesis, are presented. These findings are based on case study data from Project D. Finally, Chapter 2 discusses the additional findings together with the contributions from the three journal papers.

Chapter 3 presents an example and a guide to practitioners of how to implement the many practices and contextual changes needed for a manufacturer to effectively develop digital-physical products. The implementation process described is based on case study data from COMP.

Chapter 4 concludes the thesis by returning to the thesis objective concerning how to effectively develop digital-physical products based on the contributions presented in the thesis. Importantly, this chapter provides a number of recommendations to practitioners.

Finally, Chapter 5 presents critical reflections regarding the research methods, discusses the limitations of the present study and proposes directions for further research.

To get the best understanding and best possibility to relate (Bassey, 1981) to the specific contributions and the context in which they apply, researchers and practitioners are recommended to read the three journal papers listed in Appendices A, B and C. Practitioners are also recommended to pay extra attention to Section 4.3, which lists a number of recommendations for practitioners. For readers trying to get an overview of the current body of knowledge concerning digital-physical product development, reading Chapters 1-4 will suffice.

CHAPTER 2. HOW TO EFFECTIVELY DEVELOP DIGITAL-PHYSICAL PRODUCTS?

This chapter presents the findings reported in the three journal papers as well as additional research that contribute to addressing the thesis research objective. The additional research is based on the same case study data that was collected as described in Hendler (2020). Thus, the aim of this chapter is to present the full contribution from the analyses based on the five digital-physical projects studied within COMP, which all illuminate the *how* question implied by the objective *to explore how to effectively develop digital-physical products*. At the end of this chapter all the contributions are discussed.

2.1. CONTRIBUTIONS FROM HENDLER AND BOER (2019)

Title: "*Digital-physical product development: A review and research agenda*"

Research question: "*Which development practices and context effectively support the digital-physical development process?*"

The literature review reported in Hendler and Boer (2019) analyses the existing body of literature on digital-physical product development and results in nine findings (see below). This body of literature have lightly been summarised in Section 1.4 Theoretical background. The findings in Hendler and Boer (2019) not only provide an initial description of digital-physical product development and its context, but also outline key constructs and relationships which enable the establishment of a research model (see Figure 4) as well as a research agenda. This research model and agenda in Hendler and Boer (2019) provide a basis and a guide for the subsequent exploratory research presented in this thesis, which further illustrate the model with propositions, examples and explanations, as well as additional model details. Figure 4 shows the research model developed in Hendler and Boer (2019) and relates the findings from the literature review to the research model constructs and relationships that they describe.

Finding 1: "*Digital-physical product development is characterised by a mixed materiality and a high degree of complexity, diversity, interdependence and uncertainty, which requires manufacturers to rethink existing, and develop new, product development practices"* (Hendler and Boer, 2019).

Finding 2: "*Digital-physical product development predominantly involves separate and different digital and physical development practices and organisations*" (Hendler and Boer, 2019).

Finding 3: "*Physical and digital development deploy significantly different practices that are predominantly explained by differences in uncertainty, materiality and product architecture. Digital development is optimised for fast feature delivery, effective exploration and fast adaptation using agile development methods with late binding. Physical development is optimised for efficient component development, stable exploitation of existing investments, manufacturability and unit cost while coping with long lead time processes using a firm-centric, linear development process with early binding*" (Hendler and Boer, 2019).

Finding 4: "*Differences between digital and physical development complicate successful combination and it is often the software development practices that adapts to the requirements of the physical development practices*" (Hendler and Boer, 2019).

Finding 5: "*Despite differences in practices complicating their successful combination, some authors observe that the digital immateriality and development practices complement the physical product development practices by mitigating some uncertainty*" (Hendler and Boer, 2019).

Finding 6: "*Some literature advocates making the physical product development practices more agile. However, there is a scarcity of literature investigating this possibility or proposing other mechanisms to combine or reconcile the two processes, and their effects on the overall process*" (Hendler and Boer, 2019).

Finding 7: "*Literature does not provide clear guidelines for balancing the levels of integration and differentiation between software and physical product development in a digital-physical product development process*" (Hendler and Boer, 2019).

Finding 8: "*The literature suggests that the product development context within a traditional manufacturer, including its strategy, organisational arrangements, culture, processes outside the product development function, and its business model, is not able to successfully support, and needs to be adapted to, the requirements of digital-physical product development. However, although several bits and pieces have been proposed, only little operational insight exists into the changes required*" (Hendler and Boer, 2019).

Finding 9: "*Literature on digital-physical product development is emerging but the set of topics addressed is highly scattered and incomplete. There is no coherent body of theory on 1) the practices and context required to effectively combine digital and physical product development and 2) the capability to find and, then, implement these practices and their context effectively*" (Hendler and Boer, 2019).

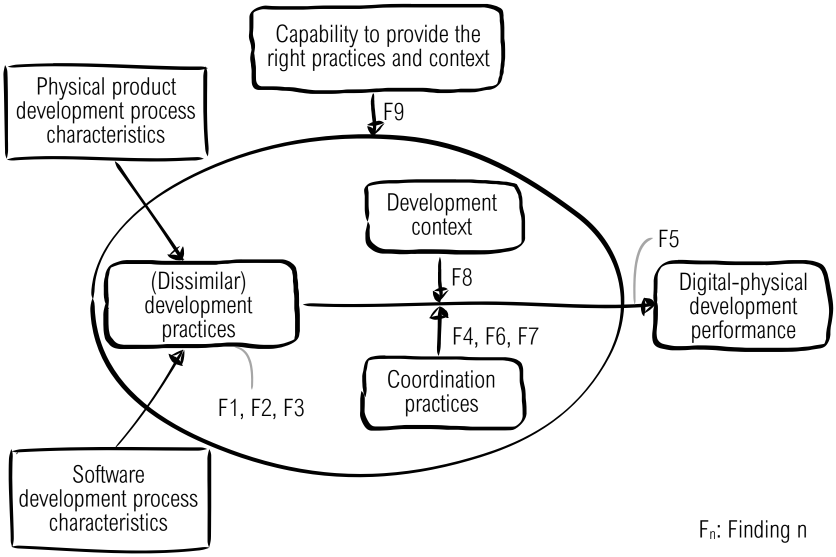

Figure 4 Research model (Hendler and Boer, 2019)

In summary, the contribution of Hendler and Boer (2019) is instrumental for research concerning how to effectively develop digital-physical products. It establishes that although the body of literature is emerging, scattered and immature (Finding 9) it provides some early descriptive theory of digital-physical product development for further validation.

Figure 4 shows the research model centred around a set of *development practices* consisting of the combined, but separately executed and largely *dissimilar* digital and physical product development subprocesses and their *characteristics* (Finding 2). A key difference between the digital and physical development subprocesses is that digital development tends to be optimised for adaptability to suit high uncertainty and complexity, whereas physical development is optimised for stability to, essentially, maintain low unit cost, enabled by, relatively, more stable markets and technologies (Finding 3).

The two processes can be combined using *coordination practices*. This combination is challenged by the dissimilarities between the digital and physical development practices. To overcome these challenges, digital development often adapts to physical development (Finding 4). Importantly, Hendler and Boer (2019, Appendix A, p. 180) find that the "*coordination practices moderate the relationship between the dissimilar development practices and the overall digital-physical development performance"* (e.g. Kuwashima and Fujimoto, 2013). However, the literature is scarce in terms of which coordination practices are more effective (Finding 6) and to what extent the digital and physical development practices should be integrated to optimise overall process performance (Finding 7). Additionally, Finding 8 indicates that the *development context* may moderate the relationship between the development practices and their performance. Hence, the combined digital-physical development practices pose new management challenges in terms of how to combine the subprocesses, but *also* with respect to the differences in materiality (tangible vs. intangible) and the challenging combined process characteristics in terms of high levels of complexity, uncertainty, interdependence and diversity (Boer and During, 2001) (Finding 1).

As an instrument for further research, the model outlines a research agenda with three areas regarding how to effectively combine digital physical product development (Hendler and Boer, 2019):

1. Effective coordination practices (Findings 2-7).
2. Suitable practices and a context that fit the process characteristics (Findings 1 and 8).
3. The capability to identify these practices and context and implement them (Finding 9).

2.2. CONTRIBUTIONS FROM HENDLER (2019)

Title: "*Digital-physical product development: A qualitative analysis"*

Research objective: "*To identify effective development, coordination and contextual practices that support the combined digital-physical development process*".

With a starting point in the research model (Figure 4), Hendler (2019) explores research areas 1 and 2 above, concerning suitable coordination practices, development practices and context. Based on data from projects A, B and C, the research model is further illustrated by evidence in the form of twelve propositions (see below).

Proposition 1: "*Compared to physical product development, the digital development process is characterised by a higher degree of uncertainty, a lower degree of diversity and digital immateriality, which allows for an adaptability-optimised development process of short, iterative development cycles with predominantly cross-functional teams, empowered decision-making, one product vision holder, a floating scope, short development cycles, late binding, short up-front planning, and several releases per product*" (Hendler, 2019).

Proposition 2: "*Compared to digital development, the physical product development process is characterised by a lower degree of uncertainty, a higher degree of diversity and a physical materiality, which allows for a stability-optimised development process of one long development cycle with a large extent of functional unit grouping, hierarchical and consensus driven decision-making, multiple product vision holders,* *a highly formalised and high-level, schedule-bound development process, early binding, extensive up-front planning, and one launch per product*" (Hendler, 2019).

Proposition 3: "*With high interdependency between digital and physical product development, imposing the early binding typical of physical development is limiting the subsequent exploitation of new knowledge in digital development, hence, reducing the digital adaptability and the potential value of the digital-physical product*" (Hendler, 2019).

Proposition 4: "*Digital development can adapt easier to the requirements of the physical development process as well as absorb some of its undesired variability, without causing a significant quality decrease of the product*" (Hendler, 2019).

Proposition 5: "*Supporting and even accommodating more agility in digital development (if not already fully adaptability-optimised) helps software development to adapt to the increased uncertainty from combining with physical product development"* (Hendler, 2019).

Proposition 6: "*In case of a high degree of interdependence, the physical product development process is bound to experience high levels of exception management and can benefit from building more flexibility into the process, including later binding and slack, to accommodate the added uncertainty from the digital development process"* (Hendler, 2019).

Proposition 7: "*When combining a physical stability-optimised product development process and a digital adaptability-optimised development process, either the former must become more adaptable, the latter must become less adaptable or both need to change, which may reduce the performance of one or both subprocesses but should lead to optimal performance of the overall process*" (Hendler, 2019).

Proposition 8: "*If digital and physical collaborate towards early physical binding, digital development is more likely to be able to successfully adapt to the early binding and design constraint from the physical product development process*" (Hendler, 2019).

Proposition 9: "*To avoid faulty assumptions and, thus, ineffectiveness, digital-physical product development can benefit significantly from ensuring cross-functionality, good collaboration skills, a shared language, and understanding of schedule and design constraints, the cost of delay, the impact of uncertainty and the cost of change associated with that*" (Hendler, 2019).

Proposition 10: "*In order to achieve a performance gain from combining the digital and the physical product development processes, managing the trade-offs between* *these processes requires close collaboration and effective communication*" (Hendler, 2019).

Proposition 11: "*Compared to traditional physical product development, digital-physical development is likely to involve a higher degree of uncertainty, interdependence, complexity and diversity that, coupled with the digital materiality, requires changes in product development practices, including rethinking marketing strategies, becoming more externally oriented, developing new testing methods, organizing the project to include digital competences at all levels, and focusing on product architecture and dependency mapping*" (Hendler, 2019).

Proposition 12: "*Compared to traditional physical product development, digital-physical development is likely to involve a higher degree of uncertainty, interdependence, complexity and diversity that, coupled with the digital immateriality, requires changes in the development context, including business model innovation, rethinking marketing operations, establishing post launch operations and new digital quality acceptance criteria, rethinking product platform(s), investing in digital tools, and ensuring digital competences for project governance and support functions including marketing, business model development and purchasing*" (Hendler, 2019).

In summary, Hendler (2019) strengthens the research model by illustrating a number of its constructs and relationships (see Figure 5).

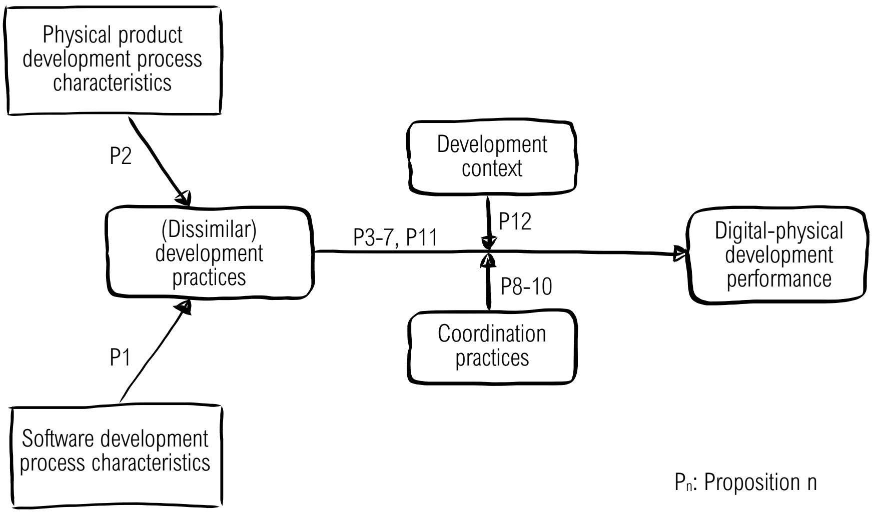

Figure 5 Simplified research model with propositions from Hendler (2019)

Empirical evidence, presented in the paper, shows that the digital and physical development processes are different in terms of their characteristics and, consequently, their development practices (Propositions 1 and 2). Importantly, when combining the physical stability-optimised development and the digital adaptability-optimised development under conditions of significant levels of interdependence, trade-offs must be made to achieve optimal performance of the overall process: either physical development "*must become more adaptable*", the digital development "*must become less adaptable or both need to change, which may reduce the performance of one or both subprocesses"* (Hendler (2019), Proposition 7). Confirming the finding from Hendler (2019), digital development adapts the most, and seems to be able to adapt easier and with a fairly low performance detriment (Proposition 4), despite committing to earlier binding and becoming less adaptable (Proposition 3). Still, such a combination causes "*the physical product development process ... to experience high levels of exception management*", which calls for less stability (Hendler (2019), Proposition 6). Combining agile processes with stability-optimised ones also seem to lead to moderate benefits in terms of the combined process system that is better able to adapt to the increased uncertainty and variability (Propositions 4 and 5). In addition to the combination requiring various trade-offs in one or both of the subprocesses, new practices are needed to adapt to the changed and more challenging process characteristics of the combined process (Proposition 11). Hendler (2019) reports evidence for advantageous coordination practices to manage the trade-offs, including early and close cross-functional collaboration (Proposition 8, Proposition 10), effective communication (Proposition 10), a shared language, and understanding of each other's constraints and motivations (Proposition 9). Finally, the cases show that many changes in the manufacturer's context are required, such as rethinking its business model, product platform(s) and marketing operations, establishing post-launch operations and ensuring digital competences for project governance committees, for example (Proposition 12).

Trade-offs seem inevitable. However, Hendler (2019) finds that three strategies may help successful digital-physical product development (Hendler (2019), Appendix B, p. 215):

1. "[Adapting one or] *both of the subprocesses to the other.*
2. *Effective coordination between the two subprocesses.*
3. *Implementation of new development practices and a suitable development context*."

The theoretical and practical implications of the contributions of Hendler (2019) in terms of context, development and coordination practices align with and complement the findings from Hendler and Boer (2019). See Figure 6 for a more graphical interpretation of the key findings from Hendler (2019).

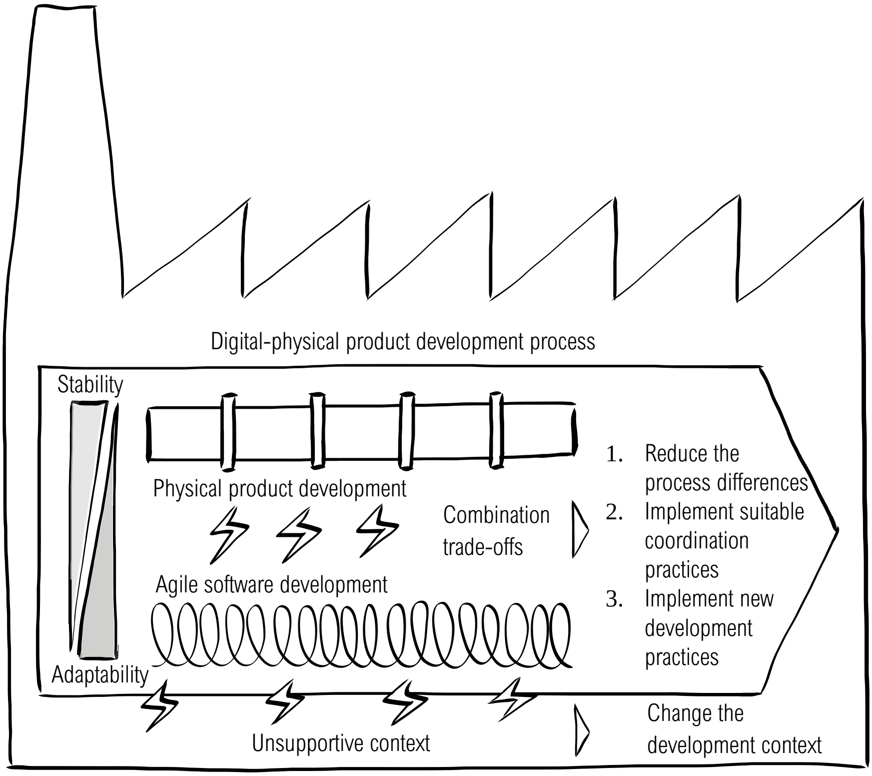

Figure 6 Accommodating digital-physical product development, manufacturer.

2.3. CONTRIBUTIONS FROM HENDLER (2020)

Title: "*Exploring coordination practices in digital-physical product development*"

Research objective: "*To explore different coordination practices in digital-physical development and their consequences for companies traditionally relying on physical development.*"

Hendler (2020) focuses on research area 1 identified in Hendler and Boer (2019): the ability of coordination mechanisms to moderate the relationship between the (dissimilar) development practices and their performance. Using data from two digital-physical development projects, projects D and E, Hendler (2020) provides descriptive operational theory via specific examples of how to coordinate digital-physical product development. The theory is summarised in four propositions which further illustrate the research model (Figure 4). For the sake of clarity, these four propositions are re-labelled from Propositions 1-4 to Propositions 13-16 in this thesis.

Proposition 13a(1a): "*The agility-optimised digital and stability-optimised physical development processes deploy different development cycle lengths (e.g. late versus early binding), planning practices (e.g. stories vs. man-hours), language and mindsets*" (Hendler, 2020).

Proposition 13b(1b): "*The uncertainty, diversity and interdependency of the combined digital-physical development process are higher than those of the individual processes*" (Hendler, 2020).

Proposition 13c(1c): "*The association between the combined digital-physical process and the performance of that process is moderated by the practices deployed to coordinate the digital and physical development subprocesses*" (Hendler, 2020).

Proposition 14(2): "*Coordination through standardisation of process (e.g. integration points), output (deliverables) and skills (roles, responsibilities) enables better informed stability-adaptability trade-off decision-making which, in turn, moderates the association between the combined digital-physical process and its performance*" (Hendler, 2020).

Proposition 15(3): "*Coordination through standardisation of process in the form of a standardised meta-process of cadenced coordination events, combined with empowered and informed individuals, facilitates mutual adjustment, which enables better informed stability-adaptability trade-off decision-making*" (Hendler, 2020).

Proposition 16(4): "*Effectively coordinating digital-physical product development involves facilitating ongoing cross-functional learning about processes, content and mindsets, and adapting coordination practices accordingly*" (Hendler, 2020).

In summary, Hendler (2020) takes its starting point in the observations that physical and digital development tend to use different coordination practices and that the literature is immature concerning which coordination practices to use when combining the two. Proposition 13 calls attention to the need to fit coordination practices to the levels of diversity, uncertainty and interdependency in the development process of digital-physical products, and to ensure that these practices can accommodate the differences between the two subprocesses in terms of different standards, planning practices, mindsets, and late versus early binding. Propositions 14 and 15 suggest that effective digital-physical coordination involves two different coordination practices: standardisation of process, output and skills to accommodate the stability needed for efficient physical product development as well as deployment of agile coordination practices. The agile coordination practices constitute a coordinating meta-process of cadenced events, such as scrum events and a version of program increment (PI) planning from the Scaled Agile Framework (SAFe). This meta-process enables frequent mutual adjustment, which allow adaptability and the possibility that the differences between digital and physical product development are negotiated continuously and effectively. Figure 7 illustrates an example of key elements of this solution. The figure shows how the subprocesses follow either agile methods or standardised, plan-driven schedules, which are coordinated via an overall project coordination meta-process. This example therefore illustrates a type of hybrid stability-agility development model.

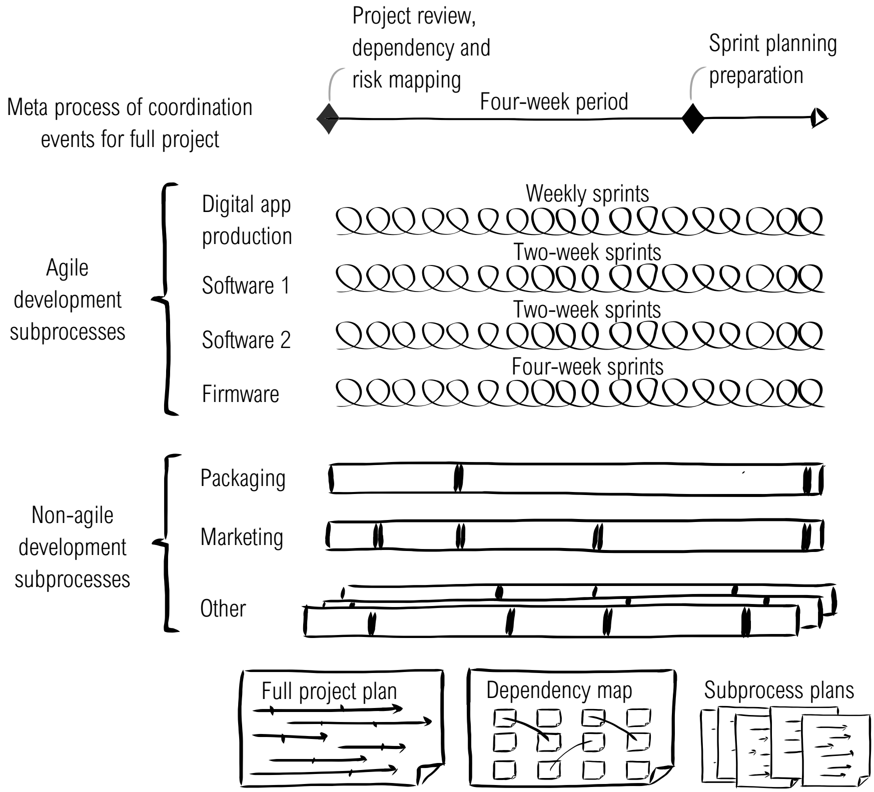

Figure 7 Key elements of a digital-physical project coordination example

Finally, Hendler (2020) finds evidence for the importance of addressing conflicting mindsets and ensuring digital-physical cross-functional learning about both the process and its content, as well as ensuring ongoing adaptation of the coordination practices to such new learning (Proposition 16).

2.4. DISCUSSION OF THE PAPERS' CONTRIBUTIONS IN RELATION TO THEORETICAL GAPS

The three papers provide and illuminate a research model with a total of nine findings, which summarise the existing literature, and sixteen propositions based on evidence from five digital-physical product development projects. Additionally, the papers provide a platform for digital-physical product development research beyond the scope of this thesis, to explore the research model constructs and relationships in different contexts and find further evidence to validate or dispute the proposed propositions.

The theory proposed in the three papers describes a suitable context as well as development (Hendler and Boer (2019) and Hendler (2019)) and coordination practices (Hendler (2019) and Hendler (2020)), which correspond with research areas 1 and 2 below, as proposed in Hendler and Boer (2019):

1. Effective coordination practices.
2. Suitable practices and a context that fit the process characteristics.
3. The capability to identify these practices and context and implement them.

With these contributions Chapter 2 seek to address the question of how to effectively manage digital-physical product development. However, to answer this question more attention is needed to research area 2. Specifically, one of the three complementary strategies for how to combine digital-physical product development, as suggested in Hendler (2019) (see Section 2.2) is: "*Adapting one or both of the subprocesses to the other*" to avoid costly trade-offs. This strategy leaves a key question unaddressed. So far, the literature and the case study of projects A, B and C has indicated that it is predominantly the digital development process that adapts to the physical development process. However, is this the most effective solution? To what extent can or should physical development adapt to digital? There is a scarcity of literature investigating the most effective solution, though "*some literature advocates making the physical product development practices more agile*" (Hendler and Boer (2019), Finding 6). This includes Hendler (2019) in which the three described projects experienced high levels of exception management and could therefore benefit from more adaptability (Proposition 6). Finally, the literature shows an increasing interest in agile methods for the development of physical products (e.g. Conforto et al., 2014; Heeager et al., 2016; Rigby et al., 2016).

Thus, to more fully address the heading of this chapter concerning how to manage digital-physical product development, the remaining part of Chapter 2 addresses the gap related to which subprocess can be adapted to optimise the overall digital-physical product development performance.

Another gap in the research relates to research area 3: Capability to provide the right practices and context (see Figure 4). None of the existing literature, including the three papers in Appendix A-C, provide clear practical examples or models for how to provide this capability (Finding 9). To address this gap, Chapter 3 explores how to build the necessary capabilities.

2.5. MORE ADAPTABLE PHYSICAL PRODUCT DEVELOPMENT

2.5.1. INTRODUCTION

Agility has been described as the ability of an enterprise to respond quickly and successfully to change (McGaughey, 1999), i.e. it provides for rapid system reconfiguration in the face of unforeseeable changes (Bernades and Hanna, 2009). What can be changed, first and foremost, when applying agile software development methods is the product specification or list of features in order to adapt to emerging and changing requirements (Cohn, 2010). Hence, an agile approach to organizing enables more adaptability in process outcomes. Similarly, the stability sought after in physical product development is, first and foremost, concerning the product specification or design. In a relatively stable market, early and stable binding of the product design enables having a predictable and highly optimised development and manufacturing system, which results in a low unit cost (Svahn and Henfridsson, 2012). Stability, in terms of repeatable tasks, particularly in the manufacturer's development execution phase, also enables the exploitation of matured, specialised and highly standardised work routines and competences across development, manufacturing and support functions, which again enables high efficiency and a low unit cost (Svahn and Henfridsson, 2012).

Like the software industries experienced in the 1990s (Rigby et al., 2016), manufacturing industries are currently experiencing a shift in their markets towards more complexity (Morieux and Tollman, 2014) and uncertainty in product requirements, which call for more agility (e.g. Takeuchi and Nonaka, 1986; Conforto et al., 2014; Svejvig and Andersen, 2015; Vedsmand et al., 2016). The product digitalisation trend only adds to the relevance for manufacturers to look into agile development practices due to digital-physical product development being characterised by relatively higher degrees of complexity and uncertainty (see Finding 1, Hendler and Boer, 2019). Adopting agile practices in physical product development could simultaneously reduce the challenging differences between digital and physical product development practices. Accordingly, manufacturing companies and the agile community are experimenting with agile practices for physical product development. Conforto et al. (2014, pp. 30-31) demonstrate that a number of enablers of agile practices are missing in manufacturing companies "*such as: the restriction to assign full-time dedication project teams; the challenge of co-locating all project team members; the difficulty in creating large multidisciplinary teams (with all project competences involved); the challenge of involving customers with a high degree of influence in project development; and the most superficial involvement of suppliers*." They therefore suggest the need for a hybrid approach.

According to Proposition 7 (Hendler, 2019), when combining physical and digital development processes, "*either the former must become more adaptable, the latter must become less adaptable or both need to change*" to optimise performance of the overall digital-physical product development process. Proposition 6 suggests that more adaptability in physical product development could help the combined digital-physical product development to accommodate the increased uncertainty stemming from the digital component. As stated above, literature on this topic is scarce, which necessitates further exploration of the extent to which physical development can or should become more adaptable. Thus, the objective guiding the research reported in the remainder of this chapter is:

To explore how and to what extent it is feasible for the physical product development process to become more adaptable to the digital adaptability-optimised development process in order to optimise the performance of the combined digital-physical product development process.

This objective aims at further illustrating the research model (Figure 4). Furthermore, the research is focused on the execution phase, i.e. *after* the front-end development, in which the need for stability of the physical development process is significant.

2.5.2. METHOD

In 2017, COMP started a digital-physical project that was focused on digitalising a core product for a large and global market. The project had an ambitious sales target and was from the beginning behind schedule due to a previously scrapped concept. With stretched targets and with the insight that this project was going to develop and deploy new-to-the-world digital-physical technologies with only little digital-physical product development experience in the company, management urged the project to look into agile development methods. COMP also selected the project to collect and share new learning about deploying agile practices. Accordingly, a team of two agile coaches was engaged to help implement new suitable practices, beginning in the front-end. The thesis author was one of the agile coaches.

Based on convenience sampling, the case study method is used in combination with action research with the described project as the unit of analysis. The project is described in Hendler (2020) as Project D. However, Hendler (2020) only analyses and describes the data from a coordination perspective.

To recap, Project D combined a manufactured product with a mobile device app that was developed by an external software company. The digital and physical product components were purchased by consumers as one integrated product. The user downloads the app on a mobile device and uses it together with the physical product to achieve better product performance. Hence, COMP did not need to develop hardware or firmware to realise the product. Only a consumer facing software app with backend and a new line of physical products were developed. The project consisted of a front-end, execution and live phase. The action researcher developed concepts for how to apply agile practices, coached the project management team and prepared and facilitated agile practices. Furthermore, she helped to capture and share learning, and was co-located with the project team for two months during the front-end and three months during the execution phase. When not co-located with the team, the researcher was located in neighbouring offices.

According to Eisenhardt (1989) having only one case means that "*it is often difficult to generate theory with much complexity*" (p. 545) and "*Perhaps 'grand' theory requires multiple studies – an accumulation of both theory-building and theory-testing empirical studies*." (p. 547). Thus, this study is considered complementary to incremental theory building as described by Christensen (2006) and develops tentative theory, which is useful in early stages of research on a topic but requires further research.

2.5.2.1 Data collection

The data describing Project D was collected as described in Hendler (2020) (see Appendix C). To "*[s]trengthen grounding of theory by triangulation of evidence*" (Eisenhardt, 1989, p. 533), multiple data sources were used. The agile coaching involved evidence collection via meetings, retrospectives, workshops and informal conversations. Being present in the project team or in neighbouring offices, the researcher had several informal conversations with project team members on the topic of how to successfully develop digital-physical products, which allowed the researcher to raise relevant topics and follow up on specific developments and new learning. Additionally, project documentation was collected including project plans, product concept drawings, team overviews, formal summaries from agile team events, emails and videos of test results. Finally, evidence was observed via various overview boards of the developing product experience, which were hanging in the project's office space. The data was collected during a 16 month period, from June 2017 to October 2018.

The iterative, two-week development cadence of Project D provided a suitable framework of planning, action and fact-finding cycles (Lewin, 1946) to facilitate the action research. Each two-week iteration concluded with a team retrospective meeting, resulting in a formal meeting summary with defined team actions to implement improvements. Additionally, mini 'plan, act, fact-finding' cycles took place, when opportune, in collaboration between the agile coaches and the project manager. Two larger reviews took place, which were focused on project operations, particularly on the agile practices. One in February 2018, where all new agile operations were evaluated based on the highly experienced project manager's perception and one in April 2018, which was a longer and more thorough retrospective with the project team.

Six formal interviews were performed as described in Hendler (2020), with open ended questions, allowing the researcher to add numerous follow up questions to achieve further details or encourage the development of explanations. The interviewees were project management, i.e. the project participants responsible for managing how the project work was done and who were responsible for the project's success. The interviews were focused on coordination practices, but also resulted in evidence supporting the research objective of this section. Also, by answering a survey, Project D's team members validated the observations of the effects of the newly implemented agile planning and dependency mapping. The survey deployed a five-point Likert scale to collect responses to five statements (see the interview and survey questions in Hendler (2020)).

The data collection was guided by a case study protocol, which, however, was subject to change and evolved as the researcher gained more insight into the project and was made aware of many new sources of data as the project unfolded. For example, many months after product launch, a final informal conversation took place with the project manager to get final reflections on perceived performance effects of the agile practices implemented. This conversation took place in December 2019 and was not planned in the initial protocol. See further data validation details in Hendler (2020), Method. In the words of Eisenhardt (1989, p. 533): "*Flexible and opportunistic data collection … allows investigators to take advantage of emergent themes and unique case features*".

2.5.2.2 Data capture and reduction

As described in Hendler 2020 (Appendix C, p. 236), "*[n]otes on observations and contextual changes, reflections on the observations and options for future actions along with photos of e.g. meeting scribbles were captured in the action researcher's diary*" of Project D (cf. Coghlan and Brannick, 2010), which amounted to 191 pages (see Appendix D for the diary template). When not actually taking part, the researcher was still present in many meetings as an observer, which allowed her to take notes and capture key quotes ensuring faithful relaying of the informants' voices. The diary reflections and the incremental project work ensured some overlap between data collection and analysis, which helped reveal helpful adjustments to the data collection (Eisenhardt, 1989). All quotes captured in the researcher's diary were marked as such and the informants' names were noted (Gioia et al., 2012). Reflections made when reviewing other documented data during the data collection period were also captured in the diary. All interviews were recorded and transcribed in separate documents by the researcher to ensure thorough internalisation and understanding of the multifaceted project descriptions.

The key data relevant to the research objective was extracted from the emails, the action diary, interview transcriptions, survey results, and retrospective and review summaries into a spreadsheet by copying and pasting informant statements, observations and the researcher's own reflections. Each row of data in the spreadsheet was divided into the following columns to enable an initial analysis of the data:

- What did the project do, or try to do, to adapt?
- What were the performance effects?
- Key informant quotes.

This was done in a way so it was clear which data was a quote, an observation, or a reflection from the researcher. This information together with the source of the data was noted in parentheses after the individual data statements.

Data was considered relevant if it described how and to what effect (i.e. performance outcomes) the project was implementing the agile principles in order to adapt to the specific project characteristics. With an exploratory mindset, no theory or predesigned template was used to assess performance effects. Rather, the analysis remained open to all types of performance effects as perceived by the interviewees and actors, such as ease of communication, speed of decision-making, quality of decision making, increased motivation, extent of shared understanding, coordination costs, and effects on the business case such as product quality and project timeliness. According to Eisenhardt (1989, p. 536) "*Although early identification of the research question and possible constructs is helpful, it is equally important to recognize that both are tentative in this type of research ... preordained theoretical perspectives or propositions may bias and limit the findings*".

Below, example data is provided that describes some of the subjectively perceived performance effects from using scrum in the project:

Motivation and engagement increased significantly (reflection, [name], [retrospective meeting]). "Also the confidence level is much higher, both in the team and from the leadership" ([Project leader name], [review meeting]). Vendor collaboration is strong and the communication with them is happening every week at a peer-to-peer level (reflection, [name], [retrospective]). "Product feasibility and desirability keeps improving and we have gathered from the team that the incremental nature of agile has helped in this process" ([Project design manager name], [review meeting]). This was instrumental to create a shared awareness on upcoming key activities and dependencies in each of the areas in development. And it boosted significantly team motivation and their feeling of belonging ([Project leader name], [review meeting])…

This initial coding resulted in 28 rows in the spreadsheet. Each row representing a specific topic.

2.5.2.3 Data analysis

Next, further grouping was made to more precisely reflect how the project managed to adapt using agile principles and practices. This analysis was done while establishing a chain of evidence to the original 28 categories and resulted in nine aggregate categories. Additionally, an analysis was made by studying the data categories to identify the agile practices the project had intended to implement, but did not find feasible. This analysis was done by reading through the 28 data categories and highlighting the relevant statements in order to be able to formulate summary statements.

2.5.2.4 Derivation of results

Based on these analyses, key conclusions were made by comparing literature and data to articulate emergent concepts and relationships between *product development practices* and *digital-physical product development performance* in accordance with the research model constructs (Figure 4). Such comparison with literature "*[s]harpens generalizability, improves construct definition, and raises theoretical level*" (Eisenhardt, 1989, p. 533). This was a highly iterative process that had started during the data analysis for Hendler (2020) and stopped when theoretical saturation had been reached (Eisenhardt, 1989). The theoretical considerations are described and discussed in Section 2.6.

Project D's project manager read the draft document and subsequently shared some concerns with some of the conclusions. This feedback effected a major change: contrary to the researcher's perception, no deliberate attempts were made in Project D by the project manager to prepare for more flexibility, i.e. change within preestablished parameters (Bernades and Hanna, 2009), after the Bill of Materials lock. Consequently, these conclusions were omitted. During this final step other conclusions were also tested against formal meeting summaries and workshop summaries. Finally, four propositions were proposed.

2.5.3. THEORETICAL BACKGROUND

This section provides a theoretical background to explore how and to what extent it is feasible for physical product development to become more adaptable to adapt to both digital adaptability-optimised development and the higher digital-physical product development process uncertainty and complexity. First, the agile digital development practices, which physical product development aims to adapt to, are described. Specifically, these are the agile practices that Project D aimed to modify and adopt. Subsequently, various practices are described that support more adaptability in physical product development processes.

2.5.3.1 Agile software development practices

Agile practices are designed for creating progress in situations with high levels of complexity and uncertainty by slicing the elephant and developing a solution incrementally and iteratively based on user feedback (e.g. Cohn, 2010; Vedsmand et al., 2016; Heeager et al., 2016). They evolved from a need to better manage software development projects that increasingly found it impossible to predict the project goal and process, accurately. Agile practices are designed based on a set of values and principles. The values include "*Individuals and interactions over processes and tools*" and "*Responding to change over following a plan*" (Beck et al., 2001). The principles include elements such as early, continuous and frequent delivery, cross-functional collaboration, trusting motivated individuals to get the job done, face-to-face communication, sustainable development pace, technical excellence and good design, simplicity, self-organizing teams, and cadenced team reflection (Beck et al., 2001). Organizing work upon these values and principles with a strong focus on customer value results in cross-functional teams, or teams of teams, that learn and make project decisions and plans accordingly (Knaster and Leffingwell, 2017). Frameworks and tools such as scrum (Sutherland, 2015), user story mapping (Patton, 2014) and big room planning sessions with teams of teams have shown to be great practices for complex and uncertain development work.

Big room planning, or PI Planning from SAFe, is typically a two day planning workshop for 100 people or more. The workshop gives everyone an overview of what everyone else is doing and the understanding of who is dependent on whom, while planning in own teams, and planning and coordinating with other teams. A common understanding of the project, its goals and master plan are prerequisites for successful big room planning (Jepsen, 2018). Central to the planning workshop is a focus on dependencies within and between teams, i.e. what do I need from you and what do you need from me to do the work?

Scrum is "*a process framework within which people can address complex adaptive problems, while productively and creatively delivering products of the highest possible value*" (Schwaber and Sutherland, 2017, p. 3). The framework consists of scrum teams and their associated roles, events, artefacts, and rules. Scrum is aimed at achieving *transparency* of the process through common standards, frequent *inspection* of progress towards goals to detect deviations, and fast *adaptation* in case of deviations outside acceptable limits. Scrum describes four formal team meetings that take place over a one to four week sprint cycle: planning, daily stand-up meeting, sprint review and sprint retrospective. The scrum roles include a scrum master responsible for the process, a development team and one product owner who is responsible for the product value, primarily through management of the product backlog: a prioritised list of product backlog items including features, functions, requirements, enhancements, and fixes. These backlog items have a description, priority, estimate of effort and often test descriptions. The product backlog is a living artifact as it is frequently updated with changes from new learning (Schwaber and Sutherland, 2017). In each sprint, the product owner and the development team collaborate to refine relevant backlog items by adding and reviewing details, estimates and priorities. High priority items are better defined than low priority items. The high priority items are refined for the sprint backlog before each sprint begins and the development team is responsible for all estimates. The sprint backlog belongs to the development team and often contains product backlog items that are broken down to user story level or tasks, and are estimated in relative T-shirt sizes or story points (Kniberg, 2015).

User story mapping is a common practice used to help prioritise the product backlog and create a shared understanding, as it provides the big picture from the perspective of a user, i.e. from a value perspective (Patton, 2014). The author behind the user story mapping method states: "*Story mapping keeps us focused on users and their experiences, and the result is a better conversation, and ultimately a better product*" (p. xxi). The method involves mapping the detailed steps of a process on sticky notes in which a user fulfils a need by applying, eventually, a company's product.

Another practice celebrated by the agile community concerns the *last responsible moment* (Poppendieck and Poppendieck, 2003), which occurs when any advantages of acquiring additional information are offset by potential risks of further delaying a decision. This originates from the Toyota Production System and just-in-time: "*Don't decide what to manufacture until you have a customer order; then make it as fast as possible*" (p. xxiii), which greatly enhances agility.

Finally, Reinertsen (2009) explains a collection of principles for flow in product development that has provided a theoretical foundation for many agile practices. He explains that the key waste in product development is the failure to optimise for economics in terms of life cycle profits. In product development, *trade-offs* are made frequently between product value, product cost, project expense and cycle time, and these trade-offs result in various levels of risk. When you trade things of value to other things of value, you should at least make an analysis of what they are worth to optimise your economics. Any analysis is better than intuition. That enables us to answer questions such as: Should we delay the app until next launch, or should we push to get something out now at a lower quality? To answer this question, it is important to quantify the '*cost of delay*', which "*enables us to decide what we are willing to pay to meet* [a] *milestone*" (Reinertsen, 2009, p. 32). Accordingly, agile practices prefer continuous delivery of value over many other considerations (Beck et al., 2001).

2.5.3.2 Adaptability in physical product development

With manufacturing companies experiencing more dynamic markets and technological development, they are learning that not all late changes in projects can be avoided (Heeager et al., 2016). Thus, more adaptability is required in physical product development. Similarly, Snowdon and Boone (2007), Remington (2010) and Lenfle and Loch (2010) describe how the management of uncertain and complex projects requires experimental learning processes involving improvisation, parallel trials, and iterative and targeted learning by doing. Lenfle and Loch (2010, p. 50) note that "*every project has parts that are relatively routine"* and they therefore use the term *"targeted flexibility*".

Conforto et al. (2014) find that a number of current practices in physical product development challenge the implementation of a fully agile project management approach. These practices include the challenge to assign full-time dedicated, full-feature (with all project competences involved) and co-located project teams. Challenges also include the difficulty of engaging customers with a high degree of influence in project development, and the, typical, arms-length involvement of partners. This corresponds with the 'halfdouble' project (Heeager et al., 2016), in which project management can be highly inspired by agile practices, but is not able to implement them as rigorously. According to Conforto et al. (2014), this calls for a hybrid project management model. Such a model is reflected in Cooper (2014) and in Vedsmand et al. (2016) and is called the Trippel A system. Figure 8 shows the model as it is depicted in Vedsmand et al. (2016). In this model, front-end work is described as 'agile'.

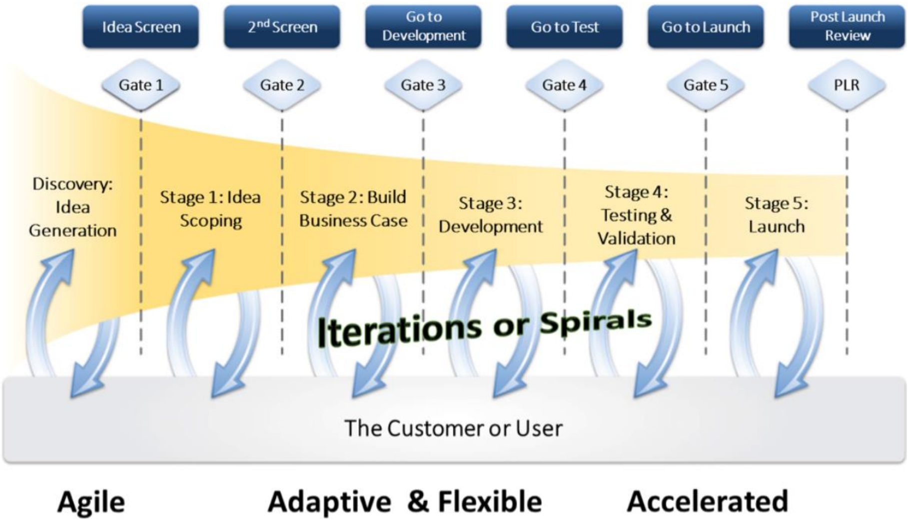

Figure 8 Cooper's Triple A stage-gate model (Vedsmand et al., 2016).

Cooper (2014, p. 21) explains: "*It incorporates spiral or iterative development to get something in front of customers early and often through a series of build-test-revise iterations. The product may be less than 50 percent defined when it enters development, but it evolves, adapting to new information, as it moves through development and testing. The system is also flexible insofar as the actions for each stage and the deliverables to each gate are unique to each development project*". The middle parts of the process, after the front-end phase, are more "*adaptive and flexible*", using scrum. Then, as the process becomes less uncertain towards the end, the focus is on "*acceleration*". Practices used for acceleration include well-staffed projects and overlapping stages. Cooper describes this hybrid model as follows: "*What emerges is a more agile, vibrant, dynamic, flexible gating process that is leaner, faster, and more adaptive and risk based.*" (2014, p. 21).

Another hybrid model is Cooper's (2016) agile stage-gate model in which the stage-gate model includes a project team that is performing scrum within selected phases of the stage-gate model. Cooper and Sommer (2018, p. 24) find that in manufacturing companies "*Agile practices may not work equally well for all stages of product development*". Figure 9 shows that the companies they studied predominantly use scrum during the development and test phases, however, with some evidence of manufacturers also using scum during front-end and the latter part of product development.

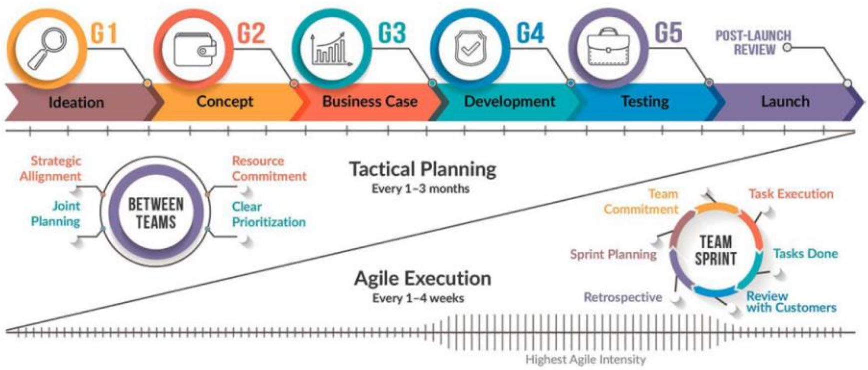

Figure 9 A typical agile–stage-gate hybrid model, with agile sprints built into stages (Cooper and Sommer, 2018)

Cooper and Sommer (2018, p. 22) find a number of challenges when combining the stage-gate and scrum, such as *"fluid versus fixed product definitions … short-term versus long-term planning cycles… management scepticism, a lack of resources to support dedicated teams, and the difficulty of producing a concrete demonstration product in a two-week sprint"*. The six manufacturing cases they studied suggest various practices to help overcome these challenges.

Thus, new literature points towards the feasibility of *physical* product development becoming more adaptable, which may help address some of the digital-physical product development challenges. However, the *digital-physical* product development literature, including the papers in Appendix A-C, shows a prevalence towards digital development adapting the most to physical and becoming less adaptable as a consequence, due to the digital interdependencies with the early and high cost-of-delay physical binding (Finding 4). Despite the new interest in product development agility within manufacturers, no literature specifically explores how and to what extent it is feasible for physical product development to become more adaptable to optimise the performance of digital-physical product development.

Below, the results of such an exploration are reported, in which the agile practices presented in this background are modified and adopted to the extent feasible, including the agile values and principles (Beck et al., 2001), organising emergent work in cross-functional teams, or teams of teams (Knaster and Leffingwell, 2017), scrum (Sutherland, 2015), user story mapping (Patton, 2014), PI Planning (Knaster and Leffingwell, 2017), and making trade-off decisions according to the idea of the *last responsible moment* (Poppendieck and Poppendieck, 2003), '*cost of delay*' (Reinertsen, 2009) and value (Beck et al., 2001).

2.5.4. RESULTS

The results are divided into three subsections, each resulting in one or two propositions. The first subsection presents the collection of the specific agile practices that were implemented in Project D, i.e. practices implementing agile principles. The second subsection presents evidence supporting the need for a more gradual physical binding. Finally, the third subsection presents evidence showing the cost of adaptability and the extent to which it is feasible for physical product development to become adaptable.

These three sections are based on an empirical analysis describing how and to what effect (i.e. performance outcomes) the project was implementing the agile principles in order to adapt to the specific project characteristics. Table 3 lists the 28 initial categories together with the corresponding nine aggregate topics as described in the method section above.

Table 3 The two levels of data categories

28 initial topics		**9 aggregate topics**
1.	Shortening lead times	Reduce physical lead-times and earlier binding
2.	Some software driven design decisions	
3.	Scrum	Iterative and incremental scrum process to adapt to uncertainty and complexity
4.	Small batch size means that sequence matters (fast feedback, reduce risk, fast learning, architectural basics first)	
5.	Fast feedback	
6.	Mature digital and physical separately, but with transparency and frequent integration	
7.	Emergent and flexible project planning	Coordination and emergent and flexible planning
8.	Dependency mapping	
9.	Mutual learning	
10.	Heavy coordination	

11. Fast decision making and empowered project management team 12. Actively used agile principles 13. Full feature mentality in project management team and in governance team 14. Full feature project teams 15. People over process 16. Agile project management meetings	Informed project management, process focus and people
17. Transparency enabled collaboration 18. Transparency through visualisation and video	Transparency and collaboration
19. Gradual binding of specification	Gradual binding of specification
20. Flexible stakeholders 21. Flexible departments	Flexible context needed
22. Separate customer testing cadence 23. User story mapping 24. More user testing	Customer centricity
25. Reducing/changing quality standards 26. Sunk cost, cost of delay + cost of hastiness 27. De-select long lead time options 28. Accepting higher risks	The cost of agility (project expense, risk, quality)

The data represented by the categories in this table is explicated in the remainder of Section 2.5.4.

2.5.4.1 Agile practices implemented

Project D was facing a significant challenge. When the project was handed over from the front-end project manager to the execution project manager, the digital-physical product concept was far from complete. The new-to-the-world digital technology was still being explored by technology concept designers, and a final proof of technology would not be possible until the external digital partner was on board the project. The partner were to utilise a version of this technology and deliver the digital product component. The physical product development was dependent on the digital technology, which was delineating how the digital and the physical components were to be integrated. To mitigate this uncertainty, the project needed to rethink the standard physical product development process. Early in the execution phase, Project D needed continued exploration, instead of starting to significantly reduce uncertainty by, for instance, locking design decisions.

The stability of COMP's standardised physical product development process has, for more than a decade, allowed the development of highly mature processes and procedures such as exception management, product data management, elaborate and detailed resource planning, and highly specialised functional skills. As stated in Chapter 1, this elaborate process standard has more than 200 scheduled deliverables across many subprocesses to achieve stability for reasons of efficiency and economy of scale across concurrent projects, supporting functions and manufacturing. COMP's product development includes a sufficient amount of slack in schedule and resources to absorb a smaller amount of delays. Despite this slack, such delays can still be very costly for a project's management in terms of time spent on stakeholder management and formal processing of schedule exception requests. Delays also has consequences for, at least, departmental efficiencies.

A smaller number of deliverables are perceived as 'hard' deadlines. These have a very high cost of delay. Some of the most critical ones are the design freeze of new physical components, the Bill of Materials lock, and the finalisation of the packaging graphics and instruction manual, as the subsequent manufacturing preparation, the manufacturing processes and the product distribution methods risk becoming much more expensive if any delays occur. See the hard deadlines in Figure 1, Chapter 1.

In this context, Project D pioneered the implementation of new practices by exploiting as much of the system's slack as possible, such as postponing the 'soft' deadlines, while striving to keep to the 'hard' ones.

Below, evidence is presented showing the project's overall approach to increasing its adaptability, how it used the scrum framework to continue the needed exploration, how agile practices were used for planning and coordination, how agile practices were used by the project management team to facilitate team learning, how the project was focused on cross-functional transparency and collaboration, and, finally, how the project, inspired by agile practices, obtained more user feedback later in the process. Subsequently, this subsection is summarised and concluded in the form of a proposition.

The project's approach to increased adaptability

The project manager had just finalised a previous digital-physical project in which the separate digital development team was not sufficiently integrated into the physical product development. He was now ready with a plan for how to change the development process based on agile principles to better coordinate digital and physical development. His plan included better accommodation of the needs of the external software company that entered the project three months into the execution phase. As the digital-physical component integration would be led by the digital partner after the product concept had matured, he stated: "*We need to make the plan that is best for digital. We will fit our own work around it*".

Additionally, the project started using the terminology: ‘the problem solving phase’, to indicate the phase in digital-physical projects that comes after the front-end phase but before the Bill of Materials lock, in which uncertainty cannot be reduced as fast as normal due to the later digital binding and need for continued exploration. Figure 10 shows how the front-end work in COMP is facilitated by agile practices, and that the processes after the Bill of Materials, i.e. after the problem solving phase, are facilitated by stability-optimised standard practices. Now, the challenge was to find an effective combination of agility and stability-optimised practices during the ‘problem solving phase’. The increased need for adaptability after the problem solving phase was dealt with later in the project as a natural consequence of also implementing a more emergent project planning practice.

The plan for the problem solving phase that was worked out with the help of the agile coaches and reviewed by project management peers, rested on a number of agility-inspired principles:

- Early, frequent and incremental delivery to maximise learning and reduce risk.
- Prioritise value generation over adhering to earlier commitments.
- Maximise the amount of work we decide not to do through prioritisation.
- Empowered, cross-functional, stable and co-located teams.
- Communication efficiency is the secret sauce (leverage on co-creation).
- Teams review and decide in a regular cadence: how to generate more value.
- Emergent and cadenced planning and coordination towards the last responsible moment.

These principles along with the considerations presented in Figure 10, guided the design of the project organisation and process to the extent to which it was feasible (see Section 2.5.4.3).

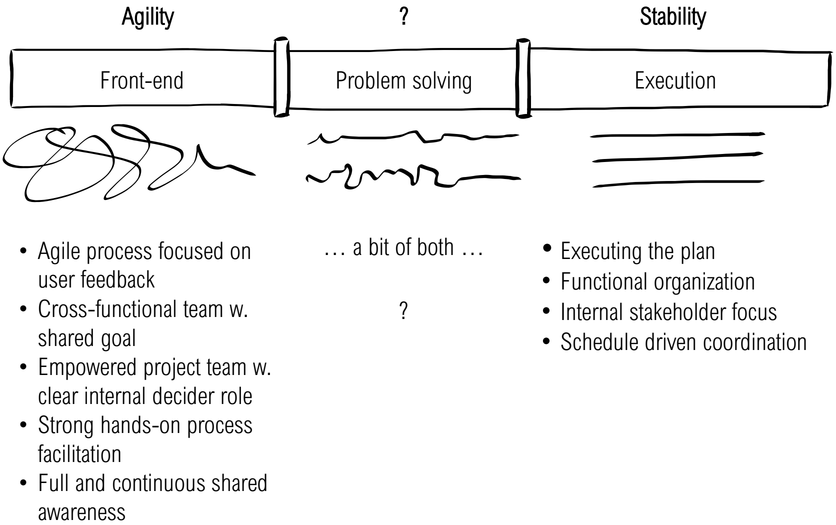

Figure 10 The problem solving phase

Scrum for continued concept exploration and development

Scrum was implemented after the front-end hand-over to facilitate the continued exploration of the digital-physical product. This meant that the project members working with these tasks were merged into one scrum team with a two-week sprint cadence with sprint planning, reviews, backlog grooming, retrospectives and daily stand-up meetings. Additionally, the full project team was joining the sprint planning sessions and the reviews of the concept development group, as a means of creating transparency and coordination centred around the core product development subprocess. These additional project members represented physical product component design, prototype testing, instruction manual design, procurement, packaging design, digital design, marketing communication design and manufacturing. The sprinting team’s tasks were prioritised to optimise for the most important learning related to the digital-physical product architecture and the physical product design. To further help the prioritisation of project tasks, a number of user journeys were mapped out. Based on these, the most valuable but uncertain steps in the user journey were prioritised the highest.

The sprint review was focused on achieving feedback from, and alignment between, project members and internal COMP stakeholders. A parallel prototyping test cadence was collecting feedback from users every two weeks. The results of these tests were presented in brief in the internal sprint reviews. To enable an empowered scrum team, several visualisation tools aided in creating transparency. A scrum board was central to the daily stand-up meetings and helped the team plan day-to-day. A high level kanban board helped the project with an overview of the maturing product solution, and which conceptual elements were in and out of scope according to the ongoing learning, and which elements still needed testing or exploration.

In this way, the project steering group was holding its breath by relying on a learning process instead of a detailed deliverables plan. The project's pace and schedule were driven by the learning speed of the scrumming project members during the first twelve weeks. The project manager added: "*In the project so far, we have been value driven, not deliverables driven, so we have not needed the normal traffic light status meetings*".

With agility and learning maximisation in mind and after the first twelve weeks, the external digital partner was brought on board. This happened via a one-day mini-sprint hosted by COMP, in which employees from both companies, digital and physical designers, were working cross-functionally in three small teams to co-create specific digital-physical integration mechanisms. The further maturation of the digital-physical product concept, design work and the proof of technology was now driven by a collaboration between the digital partner, COMP's project management team and the team of physical product designers. To follow the project manager's lead, COMP now strived towards accommodating the needs of the off-site digital developers without, however, sacrificing overall project profitability. The digital partner utilised a version of kanban and had a prototype ready every two weeks.

The project activities taking place in COMP now included physical product design, marketing planning, packaging design, instruction manual design, manufacturing planning, enterprise product data management, sales forecasting, sales channel preparation and marketing material development. Fitting the schedules of these activities to the external digital development started to get more and more difficult as the date for the scheduled Bill of Materials lock was getting closer. However, some level of agility was still achieved.

Agile project coordination and planning

Since COMP's concept team had completed its task during the first three months of the execution phase and handed over to the digital partner, the scrum activities stopped in COMP since the locus of innovation was now residing with the digital partner. Nevertheless, the bi-weekly sprint review was continued and expanded with a dependency planning meeting that included representatives for the digital partner. Consequently, this meeting functioned as a transparency, coordination, goal-setting and planning meeting, that enabled ongoing adaptation of the project's deliverables schedule. The project manager concluded: "*The dependency mapping takes the project manager out of his comfort zone, as he needs to leave it to the team to sort out the details. We simply do not have the knowledge needed for such a complex project. The team needs to collaborate too! This replaces many other small meetings we used to have*".

However, the closer the project got to hard deadlines, in particularly the Bill of Materials lock, the more difficult it was to create sufficient manoeuvrability in the plan. A project management team member explained: "*There are milestones and* [hard] *deadlines we need to keep, but in between we try to be as agile as possible, keeping things open, having check-ins, implementing feedback. ... we really cannot change the process so much, due to the high cost of delay on key integration points which, if not adhered to, increase risk, complicate stakeholder management, affects people allocations, etcetera…. After the* [Bill of Materials lock] *there is not much room for agility left…. I have learned in* [COMP] *that it is always better to run with the flow of the established process".*

Mirroring the typical need for adaptability in digital-physical projects, the digital partner stated in an email before the first co-creation session: "*Also, I should mention that* [we] *have built software for* [manufacturers] *before, so we're well aware of the long lead times needed for manufacturing, and that it is necessary to be ready with a plan B, plan C and plan D".* The project manager later explained how he, however, had not felt the need for physical product development to anticipate such contingency plans: "*We have early binding! We have to lock the Bill of Materials now to be ready for launch. After the Bill of Materials lock we only have very limited options for changing the plan. Therefore, the* [digital partner] *have had to make many decisions much earlier, we have had to front-load the digital development*". To create as much manoeuvrability in COMP's schedule as possible, the project manager pioneered a new project management approach in COMP's execution phase: "*at the latest responsible moment, we make the decision and we must consider the cost of delays very carefully*".

With these concepts in mind and negotiating the deadlines cross-functionally every two weeks in the dependency mapping sessions, the project managed to mix emergent planning with the 'hard' deadlines. These negotiations were helped by COMP's management giving the project a high priority in the portfolio. Via the ongoing, cross-functional dependency mappings many stakeholders were mutually adjusting to new information and changes to the plan. A project team member explained that with the available slack *"typically, only two to three weeks of schedule flexibility is feasible".* Partly due to the dependency mapping, the project manager did not need to negotiate flexibility or contingency plans with stakeholders due to their ability to mutually adjust and, in good time, adapt to the project needs. The project review and dependency mapping practice continued past the product launch date and into the live phase, however, with fewer people involved.

In adapting to the digital development work, COMP also made a great effort to review the digital demos coming from the digital partner every two weeks, and quickly, to make sure that the digital partner could remain agile and incorporate the feedback into the next sprint. The digital demo was typically viewed in the bi-weekly reviews, and changes in the plan could then happen accordingly. A few COMP project members had access via a mobile app to viewing daily iterations from the digital partner.

Agile project management

Configuring the project for more agility, and balancing this with the increasing need for stable deliverables towards manufacturing also included more hands-on project organisation and process adaptation by the project management team, particularly in the early part of the problem solving phase and relating to digital, such as reviewing team structures: who need what transparency and when, how do we optimise for co-location, and how can we compensate by increasing coordination frequencies and communication richness? The project manager explained these efforts while referring to the scrum and dependency mapping practices: *"suitable and stable collaboration structures become super important to ensure sufficient integration. Luckily, good ones were soon established to ensure enough transparency".* As an example of the need for more hands-on project management, the project re-introduced daily stand-up meetings after the lock of the Bill of Materials to facilitate a heavy need for cross-functional coordination due to late changes.

Accordingly, and to better be able to adapt the project to the increased degree of uncertainty the project manager explained: "*Compared to other projects* [the project management team] *meet more frequently and for a longer time. There is much more new stuff to understand and make decisions about*". The project management team itself applied a number of agile inspired practices throughout the duration of the entire execution phase: cadenced and facilitated meetings, a backlog of meeting topics that was prioritised for each meeting, visual task management on a kanban board, and more overlapping roles. As a result, these agile practices accommodated shared learning and fast decision-making. Similarly, a higher decision cadence was needed from the project steering group, who met with the project more frequently, i.e. every two weeks, and for twice the amount of time compared to the average project.

Project transparency and collaboration

Other agile practices enabled a higher level of adaptability by ensuring high degrees of transparency. These practices included a constantly updated project organisation overview to help visualise who needed to work together the most and a project schedule based on sticky notes. The project manager summarised: "*It is all about creating enough transparency for the team and stakeholders. The reason is that the project is more emergent. So we cannot just make a plan up front, that all the separate functions can work towards. We need to make sure we have the same goals and the same understanding of the current status of the project, otherwise it is difficult to collaborate. Ongoing goal setting and sharing goes on all the time, like in the review meetings. The project is dependent on our ability to create a shared culture and mindset across digital and physical. … Currently, the number of project members are around 50 across digital and physical".*

Thus, the project was characterised by heavy coordination and more time was spent to create a mutual understanding between the digital and physical design efforts through joint problem solving sessions and trying to optimise for face-to-face communication via temporary co-location through visits to each other's sites. The project management team had also staffed the project with highly skilled and curious people, to reduce the risk of people-related issues when experiencing continuous adaptation. Finally, stable mini cross-functional teams of one digital and one physical product designer were established for each product variant to ensure joint learning and joint design choices. To accommodate for the fact that the team members were dispersed across sites and time zones, video diaries were used to communicate design ideas and iterations. Videos were also used to effectively communicate results from user tests to the full team to ensure a richer and a more precise communication crucial to alignment on the product design.

User feedback

The project adapted its schedule to enable the collection of high quality user feedback on the digital-physical product three to four months before launch. However, with no option to change the physical product this close to launch, only feedback on the digital part was in focus. The timing left enough time before launch to make important changes, which also became necessary. The feedback collection was done via three tests with selected groups of users. Each test lasted fourteen days, with a period of fourteen days in-between to make necessary changes. Twelve weeks in total. This was the first time COMP had done this for a global and core product, and high risks related to product safety and information leaks needed to be carefully mitigated. To get even more learning, the digital app was released prior to the launch of the physical products to allow users to give feedback to the purely digital features provided in the app.

Summary of implemented agile practices

The list below summarises the new agile practices that were successfully implemented in the problem solving phase in order to better accommodate the digital development process and the increased project uncertainty and complexity.

- Scrum to facilitate the continued exploration of the digital technology and the digital-physical product concept during the first twelve weeks of the execution phase.
- Tasks were prioritised to optimise for the most important learning related to the digital-physical product architecture and the physical product design, as well as to reduce project risk. User story mapping was used to help with the prioritisation from a value perspective.
- Agile project management team practices with kanban task management and a prioritised backlog to facilitate effective team learning.
- A selection of agile principles to guide project management decisions.
- Ensuring high degrees of alignment in the project to enable faster decision-making and more decentralised adaptation via

    - Transparency.
    - Cross-functionality.
    - Frequent and cadenced project and management meetings**.**
    - Strong alignment through joint problem solving and knowledge sharing.
- Highly skilled and curious project members.
- Fast feedback to the digital partner's sprint iterations.
- Emergent planning via bi-weekly dependency mapping sessions throughout the projects execution and live phases.

In addition to the list above, the following practice was important to the project's agility: hands-on and ongoing project organisation and process adaptation in the first part of the execution phase in terms of who needs what transparency, which coordination mechanisms are needed and where can we facilitate more co-creation and cross-functionality? Not being a practice that is explicitly related to agility due to agile process frameworks and teams being stable, it was, however, important to enable agility in Project D to adapt to the unstable project team with changing functional experts involved, i.e. a project team with different coordination and learning needs at different points.

With these practices the project successfully adapted to the iterative digital development. However, only up to a point, which is further elaborated below in Section 2.5.4.3. The new practices based on agile principles were deployed in the product concept and product development subprocesses, which represented the biggest uncertainty. Figure 11 illustrates where agile practices were deployed in the digital-physical development process. With these agile practices, the project could respond to uncertainty by utilizing the agility of the product development team in the problem solving phase, the agility of the digital development, the agility of the project management team and, finally, the ongoing project adaptation via the cadenced dependency mapping utilizing available slack and resource prioritisation options.

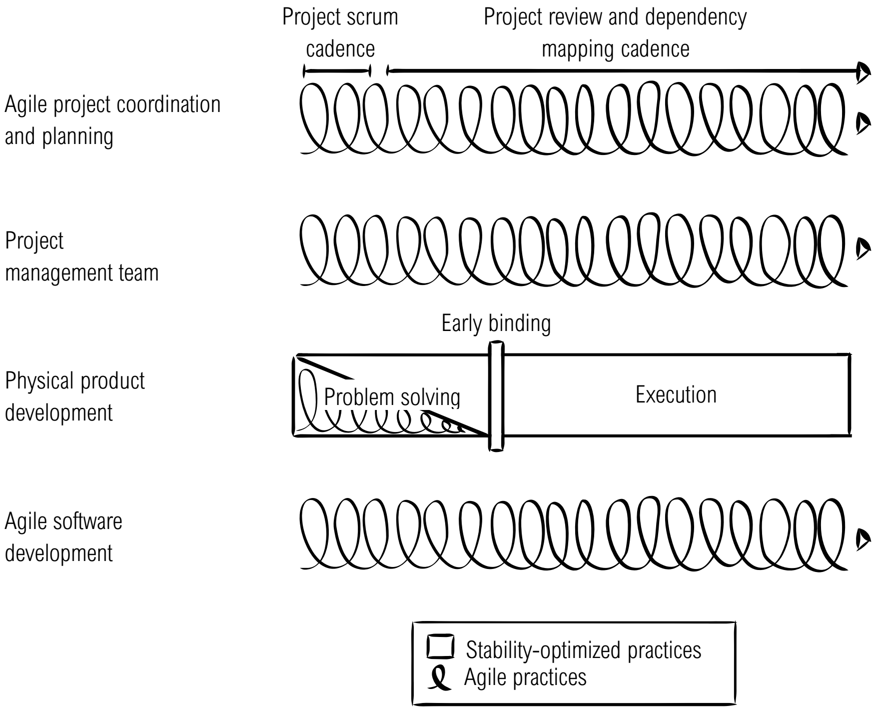

Figure 11 Agile and stability-optimized practices in digital-physical product development

The experiences obtained in Project D lead to:

Proposition 17: To optimise the performance of digital-physical product development agile practices, to increase the adaptability of physical product development, are beneficial:

- In the most uncertain subprocesses during high levels of uncertainty towards hard deadlines such as the Bill of Materials lock when the need for team learning is great.
- In the project’s management team to be able to appropriately respond to the project’s high degree of uncertainty.
- In the project’s coordination and planning mechanisms to enable transparency and cross-functional mutual adjustment to exploit available schedule and resource slack, and resource prioritisation options, throughout the project’s life.

2.5.4.2 A more gradual binding

When the digital partner was briefed on the digital-physical product concept three months into the problem solving phase, they started their incremental and iterative development process. Figure 12 shows how the product design decisions are made incrementally towards launch in digital development, whereas physical development has one key decision point after which the product specification is locked via the Bill of Materials.

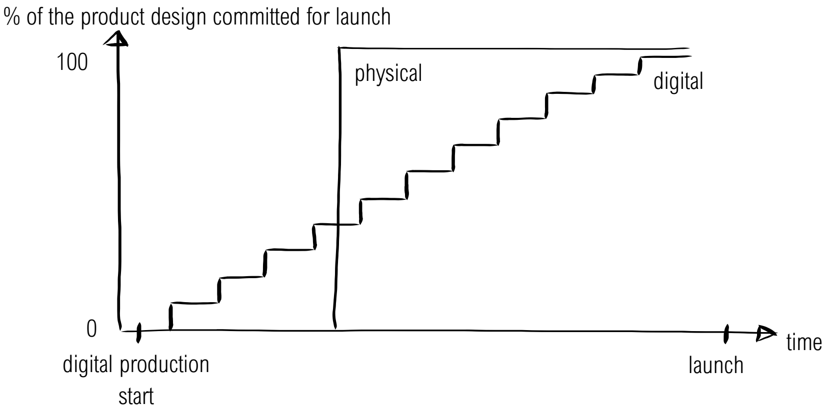

Figure 12 The relative timing of decision points for physical and digital product design commitment in Project D

In the digital development, the partner initially had to make some impactful system and tool design decisions that could not be changed subsequently without starting again. They explained to the project: "*There is a lot of stuff under the hood that is not graphic that needs to be worked out. Many systems and tools to be built. What makes the experience feel good. We like to have that established before we add* [features] *and visuals on top*". Additionally, COMP and the partner agreed to move most of the many digital design decisions, impacting the physical product design, forward before the physical Bill of Materials lock. However, due to an incremental development process many more digital design decisions were made after the Bill of Materials lock.

Thus, in Project D digital started locking the product incrementally, before physical development, which limited, albeit to a small extent, the solution space of the physical design due to digital-physical design interdependencies. This incremental locking caused a number of challenges before the Bill of Materials lock. One of the project management team members stated: "*Some* [digital] *things need to be locked too early. Some things are set in stone, now, from the* [digital partner's] *side. Then later I see that they make some larger changes that I thought were not changeable, that apparently were not set in stone. It is quite hard to understand what is fixed and* *flexible when you are not digital".* The need for intensive collaboration was evident to the project, and another project member elaborated: "*We struggle with the chicken and the egg conundrum: who leads the development? The project really tries to coordinate to make everyone happy. We want all to have a say. Every week* [the digital partner] *request information or decisions so they can move forward. So, effectively, their needs were dictating for a short period what needed to happen. To control this better we try to better use the* [documentation] *we do have to ensure better coherence. But that does not solve the problem".* The digital partner confirmed: "*We rely on certain input from* [COMP]. *We need* [COMP] *to approve it 100%, before it makes sense for us to start working on it. Otherwise, we are just wasting resources. We have limited resources and time and a fixed deadline; we cannot just add more resources that easily to compensate for such rework. This is an issue, but we are trying to work through it".*

Struggling providing the digital partner with the information they needed, some hard choices had to be made, such as asking the partner to proceed with placeholder information, and accepting the cost of rework at a later time, i.e. the 'cost of hastiness' when seen from the perspective of the physical development. The project manager explained why COMP needed to consider the whole project output, and had problems isolating and locking specific parts to benefit the interdependency with the early digital iterations: "*We need to see the full product line now, including the digital components. We need to evaluate risk based on the whole. When we lock the Bill of Materials next week, we commit large resources. It is not enough for us that* [the digital partner] *first learns about a small part of the whole, increment by increment. We would have loved to merely focus on the product now, but we also need to think go-to-market strategy and packaging, as everything is interlinked. We do not have the luxury of thinking agile, increment by increment".*

The correct timing of the digital partner entering the project was discussed. The project management team and the digital partner argued that an earlier onboarding of the digital partner coupled with strong coordination would have been beneficial to the quality of the digital-physical product concept and the proof of technology. A few maintained, for the reasons stated above regarding (too) early interdependency between digital and physical design decisions, that the entry timing Project D selected was what they preferred, or even too early. Nevertheless, getting the digital partner on board to engage with digital production prior to the physical product design lock required Project D's physical product development to start locking some product design aspects due to digital-physical design interdependency. However, this very early binding, when seen from the manufacturer's point of view, incurred an increase in project risk as physical was forced to make early decisions without having a full overview of the complete project outcome yet. The very early digital binding also caused additional costs in terms of later digital rework to replace placeholder work.

All these considerations lead to:

Proposition 18: To optimise the performance of the digital-physical product development process in which digital development starts *before* the physical product design binding, the physical product development needs to implement some incremental binding of the product design earlier than the product binding in purely physical product development projects.

2.5.4.3 The feasibility of adaptability in physical product development

Project D managed to implement more adaptability to accommodate the agile digital development and the increased level of uncertainty and complexity (relative to physical-only product development). As a result the project could continue its product exploration in the early part of the problem solving phase and better respond to new information by utilizing the agility of the product development team in the problem solving phase, the agility of the project management team and, finally, the ongoing project adaptation via the cadenced dependency mapping utilizing available slack and resource prioritisation options (see Figure 11).

The agility in physical product development beyond the Bill of Materials was, however, limited. The agile principle 'welcoming changing requirements even late in development', was helping the project only to the extent to which it did not impact project profitability, such as delaying the Bill of Materials lock. Project D locked the Bill of Materials according to schedule: "*We try to push* [the digital partner] *towards front-loading their design decisions, but many of their decisions are simply not in scope yet. We decided to just lock the Bill of Materials anyway. Pushing the Bill of Materials two more weeks would not have given us significantly less uncertainty, as there would still be much we would not know… Still, the risk is great that the physical product design will include features that will not be used by digital anyway".* The project manager concluded: "*It is significant how much risk we are accepting in this project. Our project steering group is aware of this. But at the moment it is a bit unsure to what extent the rest of* [COMP] *is aware of this. Don't know if we have communicated this well enough, or how to communicate the magnitude of a risk?"* Despite the high risk of not being able to implement significant agility to adapt to the digital development beyond the Bill of Materials lock, postponing the lock significantly would, according to the project and its management, result in much greater risks and costs. Accordingly, the digital partner was asked to make as many design decisions as possible before this lock and they were asked not to look into certain features and ideas after this point to reduce the risk of reduced quality or change in the Bill of Materials.

Despite the management encouragement to use agile practices, some agile practices proved infeasible for the project. The list below summarises the infeasible practices that were most discussed in Project D.

- Continuous digital-physical co-location was infeasible and impractical as the digital and the physical product designers depended on resources in their own respective environments, such as prototyping materials and equipment, which were located far from each other.
- Maintaining a constant and sustainable development pace was always challenged as the development pace became higher towards key deliverable deadlines.
- The agile practice of having *one* product decision maker, a 'product owner' according to scrum terminology, was difficult to fully implement, as no one in the project had the insight to make decisions for the full project across design, physical, business, marketing, technology, legal, platforms and manufacturing. Establishing a management team composed of people with sufficient expertise in these different areas was considered more feasible and in line with existing practice at COMP.
- After the digital partner started in the project, working in full feature digital-physical product teams with a digital-physical backlog was considered overkill. With digital and physical product designers and engineers having non-interchangeable competences, their ability to collaborate daily on high priority tasks on an ongoing basis was insufficient. The majority of collaboration needed was considered to be within the functional teams due to large complexities. Additionally, the functional teams were efficiently able to scale digital or physical specific solutions across the full product line, whereas a cross-functional set-up with different teams responsible for different products was considered to be slower and less focused on cross-product consistency. The project was able to compensate with a significant amount of digital-physical coordination practices instead, such as the coordinating mini teams of one digital and one physical designer for each product variant during the latter part of the problem solving phase.

With some agile practices being infeasible for the project to implement, others were feasible, but involved a performance trade-off. For example, according to some project members, the agility in the problem solving phase decreased the product quality. The physical product designers had been challenged by the late changes coming from digital and some project members believed that compromises had been made to the physical product design due to these late digital requirements. A project member explained: "*The experience is OK now. … We have had to deselect features as there has not been enough time to mature them*". Another explained "[COMP] *is used to launching top quality. A 10. Now we launch something that is a 7 or 8 or 6. This will be painful for us. And new to* [COMP]".

The agile problem solving phase was also considered to increase project risk, as the normal risk reduction process had been replaced with more exploration. Although implementing agile practices is generally considered to decrease risk due to a focus on feedback based learning loops, it requires trust in a timely progression within the learning process toward the goals set by the management. Despite worries about being able to lock the Bill of Materials in time, the project saw it necessary to do “a leap of faith”. Engaging with agile practices was perceived to increase the schedule risks in Project D. The agile practices also involved keeping a number of decisions open for longer, until the last responsible moment, which was also perceived as a risk. Nevertheless, these increased and temporary risks were, eventually, outweighed by the overall project performance gains.

As mentioned above, the more gradual and even earlier binding of some parts of the product design, resulted in an increase in project risk as physical was forced to make decisions without, yet, having a full overview of the complete project outcome. In other instances, adapting to the early incremental digital binding caused additional costs in terms of later digital rework to replace early placeholder work.

The project manager also considered the cost of more time spent on project planning, project coordination, project management and stakeholder management incurred by solving and communicating complex problems. He added: “*Of course it has had an added process cost, as the efficiency would have been higher had it been a pure physical product, but the impact on the business case is only a blip. It is insignificant compared to other costs”.*

Engaging with new agile practices, such as doing market testing three to four months before launch with a significant volume of manufactured products and engaging with ‘live’ marketing, impacted the practices in a number of supporting functions. Thus, Project D and other digital-physical projects were largely managed as exceptions in terms of many standard processes and deliverables. Concerns raised by project members and manufacturing coordinators included how many exceptions COMP could successfully accommodate as well as the impact on concurrent projects, when high priority digital-physical projects depleted departments from the best skilled people. Thus, due to a lower ability to provide detailed predictions of when the project would need resources from specific functional departments, short-notice resource requests risked to impact the performance of other projects who were counting on receiving the resources they needed as planned. This was a new situation for COMP, which used to be able to fairly reliably allocate resources many months in advance.

In summary, Project D adapted to digital and the challenging project characteristics by implementing more adaptability via agile practices. However, only to the extent to which stability was not compromised with a significant and detrimental effect on Project D’s performance and that of other concurrent projects. For Project D, the trade-offs coming with increased adaptability included a slightly reduced product quality at launch, slightly increased process cost and increased risks. The project was, however, profitable and effective in creating high consumer value. This leads to:

Proposition 19: To optimise the overall digital-physical product development process, implementing agile practices in physical product development is feasible to the extent that high cost of delay deadlines, including the early physical binding, are met so as to avoid significantly compromising the project's own performance, and that of concurrent projects.

COMP digitalised less than a quarter of its product portfolio, and, therefore, needed to uphold stability to maintain a profitable manufacturing set-up for the remaining part of the portfolio. The destabilizing effect on the product development context within COMP relates to the challenge to provide the right practices at the right time to effectively accommodate digital-physical product development (see Finding 9, Hendler and Boer, 2019). The lesson from this is:

Proposition 20: If a manufacturer is aiming to digitally enhance a significant portion of its portfolio of physical products, proactive changes to the development context should be initiated before a potential exception management overload of the company's operations results in significantly reduced performance.

2.5.5. CONCLUSION OF ADDITIONAL FINDINGS

When combining digital and physical development processes, "*either the former must become more adaptable, the latter must become less adaptable or both need to change*" to optimise performance of the overall digital-physical product development process (Hendler (2019), Proposition 7). Elaborating on this proposition, this research finds evidence for how and to what extent it is feasible for physical product development to become more adaptable in order to cope better with the relatively high degree of complexity and uncertainty of the development process of digital-physical products. First, the research shows that physical product development *can* become more adaptable and less stable by implementing agility in accordance with agile principles without significantly compromising performance. However, only to an extent (Proposition 19).

Specifically, the research finds that it is feasible to implement agile practices in the most uncertain subprocesses prior to the Bill of Materials lock to optimise the overall digital-physical product development. It is also feasible to implement agile practices in the management team of a digital-physical product development project to help the project adapt to the relatively higher uncertainty and complexity of such projects (Proposition 17). Furthermore, it is feasible to implement a more agile planning practice by cross-functional negotiations in dependency mapping exercises, implement cost of delay considerations, and exploit schedule slack *throughout* the physical product development execution phase and live phase (Proposition 17). Finally, engaging a digital partner with digital development before the physical product design binding, requires the physical product development to accommodate some incremental binding of the product design towards the binding of the complete physical product specification to optimise the overall digital-physical product development (Proposition 18).

This increased level of adaptability may come at a cost in terms of slightly decreased product quality, slightly increased process cost and slightly increased project risks compared to a purely physical project. However, the evidence in this case study showed that the project can make such trade-offs and still deliver significant consumer value and a profitable business case. Finally, the research demonstrates that if a manufacturer is aiming to digitally enhance a significant portion of its portfolio of physical products, proactive changes to the development context should be initiated before a potential exception management overload of the company's operations results in reduced performance (Proposition 20).

2.6. DISCUSSION OF ALL FINDINGS

As presented in Hendler and Boer (2019), the research model (Figure 4, Chapter 2) outlines three research areas:

1. Effective coordination practices.
2. Suitable practices and a context that fit the process characteristics.
3. The capability to identify these practices and context and implement them.

Area 3 is further explored in Chapter 3. The theoretical and managerial implications relating to areas 1 and 2 based on all the evidence uncovered in this research are discussed below.

Figure 13 is an update of Figure 5 (Chapter 2), the simplified research model, with focus on research areas 1 and 2. The model is updated with all related findings and propositions from the papers in Appendix A-C and Propositions 17-20, which tentatively describe how to effectively develop digital-physical products.

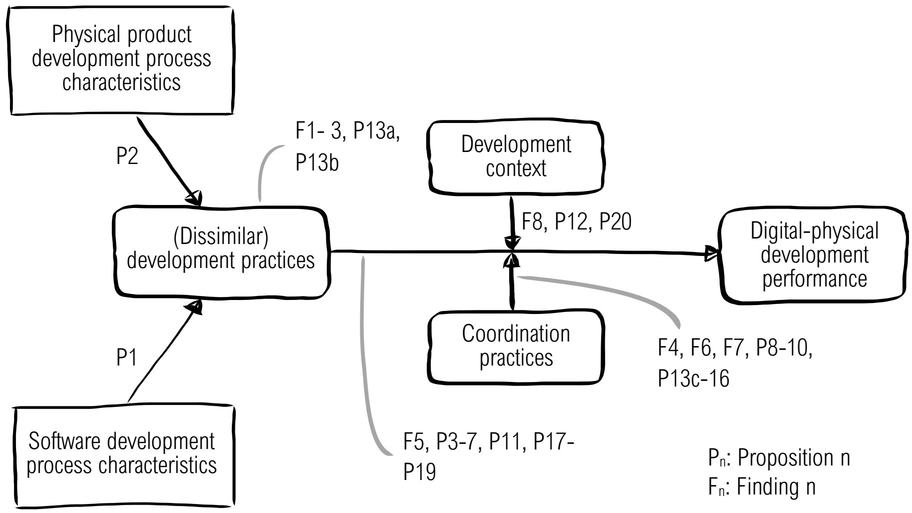

Figure 13 Simplified research model updated with findings and propositions relating to research area 1 and 2

2.6.1. EFFECTIVE COORDINATION PRACTICES (RESEACH AREA 1)

The literature review (Hendler and Boer, 2019) found that the combined process is characterised by challenging characteristics, a mixed materiality (Finding 1) and different and separate development practices (Findings 2 and 3), which require the manufacturer to rethink existing development practices (Finding 1) and their context (Finding 8, Propositions 12 and 21). In agreement with Porter and Heppelmann (2014, 2015) and Yoo et al. (2012), these findings establish the need for manufacturers to not only view product digitalisation as another innovative product development project, but as the beginning of, probably, a company transformation depending on the extent to which the product portfolio is being digitalised (Proposition 20). Even just a single digital-physical project may significantly disrupt established development and support practices (Proposition 11). This includes how product development projects are coordinated.

With different digital and physical product development practices, their combination is challenging (Finding 4). No theory exists to advice on the degree of integration of the two subprocesses (Finding 7), but most cases show a clear separation between the two development subprocesses in digital-physical product development (Finding 2). This leaves coordination mechanisms to ensure their combination.

Hendler (2020) provides two clear examples and four propositions supported by explanations to guide the new product development manager (Propositions 13-16). Based on the important notion of performance trade-offs from Reinertsen (2009) and Hendler (2019), Hendler (2020) devises how a combination of standardisation

(Proposition 14) and mutual adjustment (Proposition 15) mechanisms (Mintzberg, 1979) can result in informed, cross-functional trade-offs to find the right balance of adaptability versus stability. Contrary to Mintzberg's (1979) theory, agile practices can effectively and efficiently facilitate mutual adjustment for large groups via transparency and empowerment. This compounds the argument for digitalising manufacturers with large team sizes to engage with agile practices and ensure the availability of competences such as scrum coaches.

Project D demonstrates a specific instance of the agile stage-gate process in which only parts of agile team practices continue with great effect for as long as they are needed and deemed useful. Specifically, Project D continued the dependency mapping and cadenced reviews into the live phase. Understanding agile practices from a coordination perspective offers the product development manager a lens through which it may be easier to select the most fitting practices from large integrated frameworks such as scrum (Sutherland, 2015), Scaled Agile Framework (SAFe) (Knaster and Leffingwell, 2017) and Large Scale Scrum (LeSS) (Larman and Vodde, 2016). Thus, in COMP's digital-physical projects the coordinating meta-process of agile practices is proving to be an important addition to their standard practices for digital-physical product development.

2.6.1.1 Conclusion

In conclusion, digital-physical product development requires the manufacturer to rethink its project coordination mechanisms. Understanding and implementing agile practices with a *coordination problem* in mind can help the manufacturer to select the appropriate agile practices, which increase its product development adaptability while complementing existing coordination practices based on standardisation.

2.6.2. SUITABLE PRACTICES AND A CONTEXT THAT FIT THE PROCESS CHARACTERISTICS (RESEARCH AREA 2)

2.6.2.1 Deliberately making stability-adaptability trade-offs

Digital-physical product development is emerging as a difficult innovation management discipline, not least because it comes with an in-built challenge in terms of its dissimilar development practices. Illustrating this, Figure 14 adds further detail to the proposed research model construct: *(dissimilar) development practices*.

The adaptability-optimised digital development process and the stability-optimised physical product development process are described by different characteristics (Propositions 1 and 2). These characteristics coupled with the differences in materiality (Findings 1), seem to be able to explain why the processes are relatively optimised for adaptability and stability, respectively, i.e. two different goals. The resulting and combined digital-physical product development process is described by challenging characteristics in terms of high levels of uncertainty, complexity, diversity and complexity (Finding 1), mixed materiality (Finding 1) and dissimilar development practices (Findings 2 and 3) (see Figure 13).

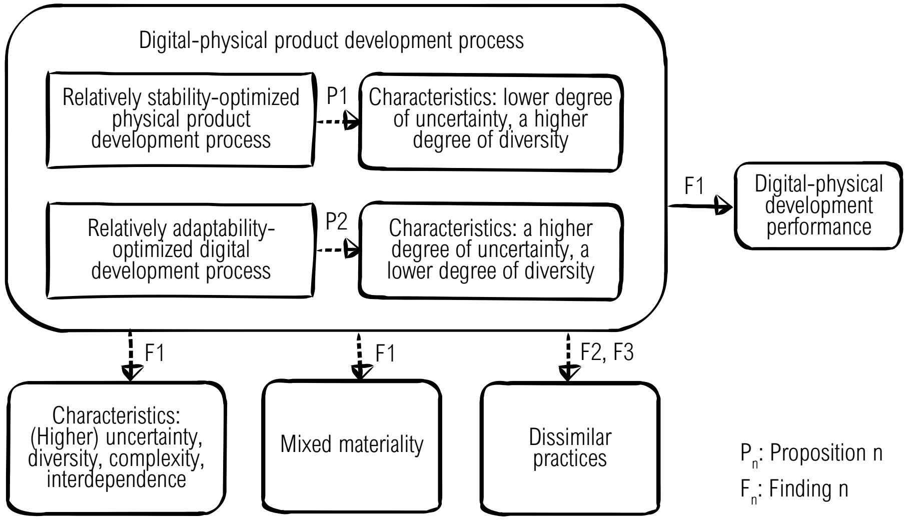

Figure 14 Dissimilar development practices in digital-physical product development – causes and effects

The in-built process dissimilarity challenges the combination of digital and physical product development (Finding 4) (see Figure 13), particularly with respect to the relatively early physical binding and the relatively late digital binding. That is, the dominant part of the digital binding usually happens after the physical binding, with some happening very close to the release date. Complementary to Svahn and Henfridsson's (2012) 'late' digital binding, a 'gradual' digital binding may be a more precise description (Proposition 18). Specifically, "*[w]ith high interdependency between digital and physical product development, imposing the early binding typical of physical development is limiting the subsequent exploitation of new knowledge in digital development, hence, reducing the digital adaptability and the potential value of the digital-physical product*" (Hendler (2019), Proposition 3). This emphasises the importance of the manufacturer to make deliberate performance trade-off decisions. Do we aim at digital adapting to the front-loading and early binding of physical product development? Do we compromise the stability of the manufacturer's operations to enable more adaptability? Do both digital and physical need to change? Thus, *central* to the challenge of digital-physical product development for both theory development and practitioners, Proposition 7 summarises that, "*when combining a physical stability-optimised product development process and a digital adaptability-optimised development process, either the former must become more adaptable, the latter must become less adaptable or both need to change, which may reduce the* *performance of one or both subprocesses but should lead to optimal performance of the overall process*" (Hendler (2019), Appendix B, p. 207).

2.6.2.2 Both need to and *can* change

Both the literature review in Hendler and Boer (2019) and the case study presented in Hendler (2019) showed that it is typically digital that adapts to physical by becoming less adaptable and committing to earlier binding (Finding 4), and that this can be done, to some extent, without causing a significant decrease of product quality (Proposition 4). Digital development seems able to create value under heavy constraints, i.e. a narrow solution space.

On the other hand, the research also finds evidence that adding an agile process capability to an otherwise plan-driven project has some positive performance effects as it helps the combined project or process system to fit the increased level of uncertainty (Propositions 4 and 5, and Finding 5). For instance, a quality error or a missed opportunity in the physical product component design that emerge late in the development process may be mitigated through fast development of a new compensating software feature.

Thus, adding an agile software development subprocess to a plan-driven project both presents challenges as well as benefits. This demonstrates the importance of paying attention to the various performance trade-offs associated with the specific dissimilarities between digital and physical product development. In projects A-E, *both* digital and physical development have adapted: the digital development has become less adaptable and physical product development has become more adaptable, either deliberately by implementing agile practices in physical product development (projects D and E), or less deliberate via reactive exception management, for instance (projects A, B and C). Both digital and physical development have adapted with acceptable project performance consequences. From a project perspective, trade-off decisions may have to be done step by step as events unfold while anticipating the need to adjust both digital and physical product development practices to become more aligned. *Adapting both processes to each other* may be the best way given current manufacturing technologies.

Doing this requires hands-on management, who continuously monitors the overall process and makes the adaptations in 1) the two subprocesses and 2) the interaction, including the coordination between them. Supporting this, Proposition 10 states that effective management of the trade-offs requires close collaboration and good communication between digital and physical, and Proposition 16 (Hendler, 2020) states that effective coordination requires "*ongoing cross-functional learning about processes, content and mindsets, and adapting coordination practices accordingly*". In Project D, the digital-physical management team, itself, deployed agile team practices (Proposition 17) to support such ongoing learning, transparency and responsiveness to the project's needs throughout the duration of the project. Also, agile project practices such as project reviews, dependency mapping and retrospectives support hands-on management. Thus, agile inspired practices may be a great vehicle to support hands-on and deliberate management when adapting both processes to each other in digital-physical product development.

Another option to effectively combine digital and physical product development involve reducing the interdependencies between the digital and physical product development subprocesses via e.g. commodity hardware platforms, software platforms (Evans, 2009) and loosely coupled architectures (Yoo et al, 2010). However, in the case of COMP, such decoupling was never fully achievable as the projects' product visions were only achievable via tight collaboration between digital and physical development due to a significant innovation ambition and a lack of established platforms to support these visions.

2.6.2.3 Making physical product development more agile

Proposition 6 summarises evidence showing that "*[i]n case of a high degree of interdependence, the physical product development process is bound to experience high levels of exception management and can benefit from building more adaptability into the process to accommodate the added uncertainty from the digital development process*" (Hendler (2019), Appendix B, p. 207). Accordingly, to explore suitable practices, Section 2.5 above explores how and to what extent physical product development can become more adaptable to optimise digital-physical product development performance. Project D found it feasible to implement agile practices to increase the adaptability of physical product development in their project management team and in the most uncertain subprocesses, including digital technology exploration, physical product design and exploration of digital-physical integration mechanisms, all of which precede the binding of the Bill of Materials (Proposition 17). Additionally, to be able to cope with the increased uncertainty, the project implemented a more emergent, agile planning practice. This was done through bi-weekly, cross-functional stakeholder negotiations, and cost of delay (Reinertsen, 2009) and last responsible moment (Poppendieck and Poppendieck, 2003) considerations, and by exploiting the available slack in the project schedule (Proposition 17).

It may be tempting for the manufacturer to contractually force digital to adapt to physical for reasons of size, stability, cost of change or tradition from pre-agile digital-physical product development where software typically played a smaller role in the product. It may also be the right decision, depending on the specific product architecture and allocation of functionality between digital and physical. However, this research has demonstrated the viability of physical product development becoming more adaptable to optimise the performance of the combined digital-physical product development process. Also, with manufacturing companies experiencing more uncertainty anyhow, the motivation to rethink their practices has increased anyway (Conforto et al., 2014).

Implementing agile practices in Project D seems to not only have helped adapt to the higher project uncertainty but also to 1) the increased diversity, by focusing on transparency and cross-functional collaboration, 2) the increased level of interdependencies, by implementing frequent coordination, as well as 3) the increased level of complexity, through using team learning to solve complex tasks, all of which are agile practices. Thus, agile practices fit processes with high levels of all four process characteristics: uncertainty, diversity, interdependence and complexity.

2.6.2.4 A hybrid agility-stability product development model

How and to what extent should physical product development become more adaptable? This research first and foremost supports both Lenfle and Loch (2010), who maintain that some parts of a project should remain stable, and Conforto et al. (2014), who propose that a hybrid approach is needed. Project D demonstrates how the project management, the manufacturer's front-end development and parts of the physical product development during the problem solving phase can successfully become more agile, while the remainder of the physical part of the project is executed according to the standard stability-optimised practices (Proposition 17 and Figure 11). In contrast, the digital part of the project is becoming more stability oriented by having to front-load a significant amount of product design decisions to coincide with the early physical binding. This hybrid approach involves that agile practices, in particular elements such as agile team structures, roles and co-location, are used in the digital process, but adapted to the needs of the physical development process.

The research also supports some aspects of Cooper's (2014) Triple A model (Figure 8), in which the agile front-end progresses into a more adaptive and flexible phase that ends in a phase focused on acceleration. Figure 15, which is inspired by that model, shows how the physical development process progresses from agility at the front-end to stability in the latter part of the execution stage. Agile practices persist throughout the digital development subprocess even after the Bill of Materials has been locked, which, however, only results in *some* adaptability in the eventual process outcomes as much of the product design has been locked at that stage. Nevertheless, maintaining the agile practices has other benefits in addition to adapting to uncertainty and enabling the software developers to continue their preferred way of working. First, software development is still highly complex, which fits agile practices (Rigby et al., 2016; Schwaber and Sutherland, 2017). Second, Proposition 4 states that digital development can absorb some of the undesired variability in physical development after the Bill of Materials lock, by, for example, mitigating a physical quality error by developing an additional software feature.

The middle phase, i.e. the problem solving phase of physical product development, must balance agility with stability to conform to high cost of delay schedule constraints (see Figure 15). In the Triple A model, 'agility and stability' is replaced by 'adaptive and flexible'. A key difference between Coopers' (2014) Triple A model compared to COMP's new practices is that the project go/kill gates are replaced by bi-weekly project steering group meetings with the agile-inspired intention of guiding and removing impediments to the project.

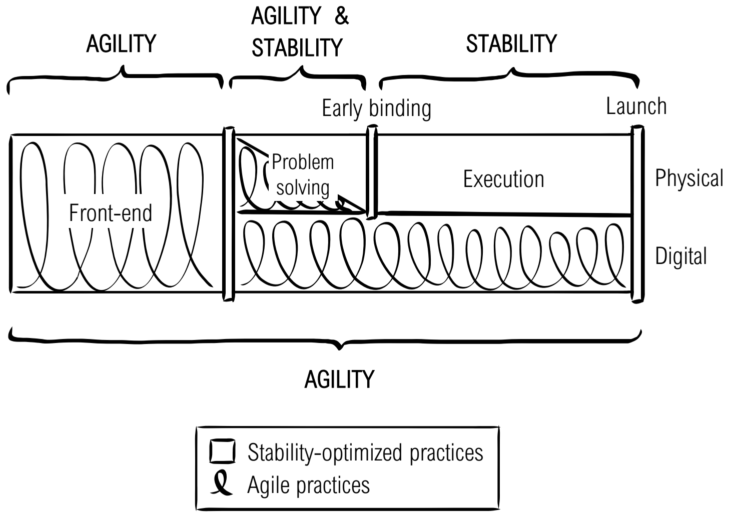

Figure 15 The nature of the development practices in digital-physical product development.

Regarding Cooper's agile stage-gate model (2016) ,which includes a project team that performs scrum in selected phases of the stage-gate model, Cooper and Sommer (2018) find that "*[a]gile practices may not work equally well for all stages of product development*" in manufacturing companies. Particularly, they find that companies predominantly use scrum during the development and test phases in Cooper's stage-gate model (see Figure 9), largely equivalent to the problem solving phase in Figure 15, in which the majority of product development and testing takes place. However, they also provide examples of companies using scrum from a project's beginning until launch. In project D, scrum mechanisms were used for the product development in the front-end and during the problem solving phase, specifically the first twelve weeks. After the first twelve weeks, selected agile practices were used, namely bi-weekly planning, dependency mapping and review, visual management, and co-location when possible. For a manufacturer, the Bill of Materials is a significant milestone, after which the cost of changes to the product increase exponentially the closer the project gets to launch. Thus, the feasibility of product learning supported by agile practices is significantly reduced. However, due to the relatively higher uncertainty of, and diversity in, digital-physical projects, and the interdependency between the physical and digital development, i.e. between COMP and its external partner(s), agile transparency and coordination in the form of bi-weekly project reviews and dependency mappings remained important even after the Bill of Materials was locked.

Cooper and Sommer (2018) also refer to the level of intensity of agile practices. Following this terminology, the level of intensity in COMP was highest in the front-end and started declining in the physical part of the problem solving phase. In the digital development part, the agile practices continued throughout. However, there may be good reasons for continued, possibly intermittent, scrum practices beyond the Bill of Materials lock, supporting for example the development of marketing materials, go to market strategies, preparing for manufacturing and price setting, particularly as this work may be interdependent with the ongoing and incremental digital development.

Thus, the agile stage-gate model seems to be a viable concept for digital-physical product development, in that it enforces a focus on stability in terms of key milestones while encouraging adaptability via agile practices in some of the stages and, for certain activities, for all stages. However, Cooper's phases does not reflect the live phase, nor the importance of the high cost of delay milestones: lock of new physical platform components, Bill of Materials lock, and lock of packaging and instruction manual graphics (see Figure 1, Chapter 1), as well as the software verification, hardware development and full stack product integration. In Project D, the first three, physical, milestones became a key project planning focus to which digital adapted to a large extent, and which limited the extent to which Project D could adopt agile practices.

2.6.2.5 Gradual binding in physical product development

In Project D the physical product development needed to accept some incremental or gradual binding of parts of the product design before they were ready to do so. This happened in the early part of the problem solving phase before the Bill of Materials lock, to accommodate some of the early and gradual digital binding (Proposition 19). Figure 16 shows this gradual binding.

The more gradual binding of the physical product specification fits suggestions from Karlström and Runeson (2006) and Eklund and Bosch (2012), and involves physical development to make some even earlier binding decisions as well as later ones while, still, front-loading many of the digital product design decisions. This gradual binding pattern may be a powerful guide encouraging practitioners to front-load architectural design decisions that are foundational to the digital-physical design, while decoupling other digital-physical interdependent decisions via product architectures and platforms (Evans, 2009). The gradual physical binding pattern may be a measurement for further quantitative or qualitative research into this topic. Additionally, Reinertsen's (2009) 'cost of delay' can be supplemented with a 'cost of hastiness', to be able to measure the effect of starting the gradual binding too early from a manufacturer's perspective.

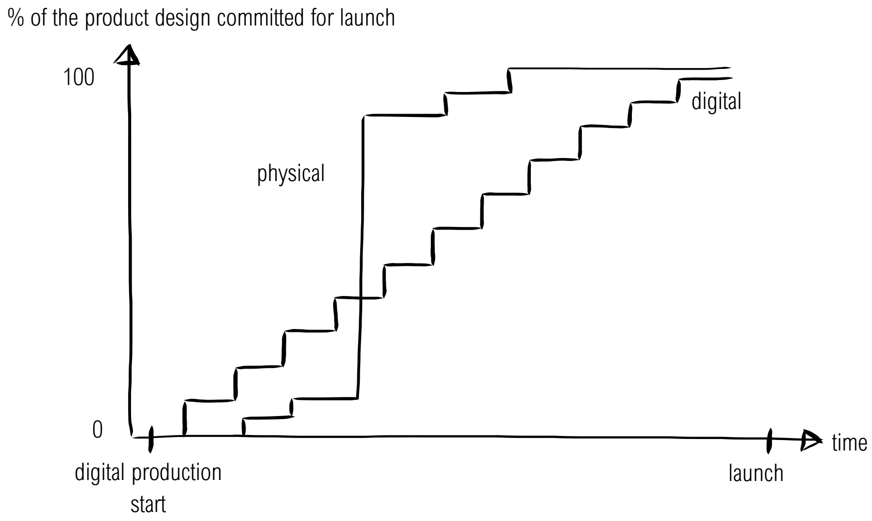

Figure 16 A slightly more gradual binding in physical product development

2.6.2.6 The cost of adaptability in a stability-optimised system

Implementing more adaptability into a stability-optimised system comes at a cost. Specifically, lower digital-physical product quality, higher project cost and risk, and potentially higher cost of concurrent projects (Proposition 20). However, these costs can be a result of deliberate performance trade-offs, as demonstrated by Project D and recommended by Reinertsen (2009), in order to optimise overall digital-physical product development performance. With these performance trade-offs in mind and in accordance with Conforto et al. (2014), some agile practices were infeasible. However, with the project management in Project D intent on implementing more agility, and educated about the principles underlying the agile practices, agile practices were implemented to the extent feasible (Proposition 22). Figure 17 illustrates the performance trade-offs made to optimise overall digital-physical product development performance.

Implementing agile practices introduced an increased risk to the project concerning the ability to control progress towards management set goals, when having to trust the outcome of the two-week sprints. Despite a hands-on project management team, the project manager still saw the new practices as a leap of faith. Additionally, keeping decisions open until the last responsible moment added risk compared to the purely physical projects. Such schedule risks contributed to informing the performance trade-offs regarding the extent of agile practices Project D decided to implement.

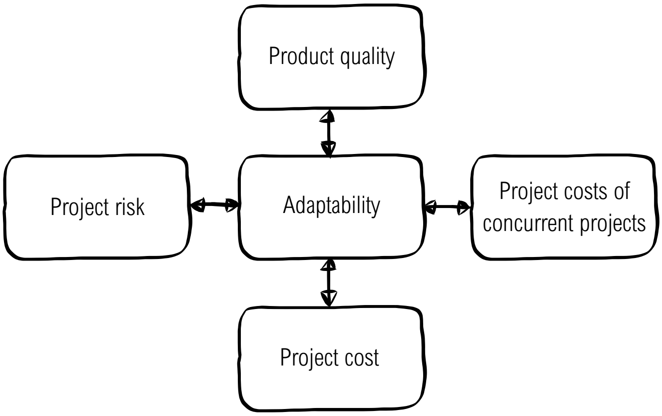

Figure 17 Performance trade-offs

Over time, the performance detriments of implementing more project agile into a stability-optimised system may be off-set by gradually implementing more agility outside the project, for instance, in project portfolio management and in functional departments. In this way, departments may be able to process both stable and uncertain demand in an effective and efficient way through, for instance, functional or component team structures (Kniberg, 2015) running scrum while supporting project demands.

2.6.2.7 Many new practices

As found in Hendler and Boer (2019), manufacturers need to consider suitable practices as well as a context that fit the characteristics of the development process of digital-physical products. Suitable practices not only concern the level of stability and adaptability, but also a number of specific functional product development practices, such as marketing, distribution, external orientation and architecture related practices (Proposition 11). Similarly, practices in the project context such as company business model innovation, establishing post launch processes, product platform management and project governance models need to change (Finding 8 and Proposition 12). This is important information for the new product development manager, who needs to avoid a situation of exception overload (Proposition 21) in the supporting organisation, due to exception requests, late changes and uncertain forecasting coming from digital-physical product development projects.

2.6.2.8 Conclusion

In conclusion, the present research provides several new insights for digitalising manufacturers regarding the management and functional practices they need to pay attention to and adapt. This includes fitting practices to the process characteristics (uncertainty, diversity, complexity and interdependency) and balancing adaptability with stability.

CHAPTER 3. CAPABILITY TO PROVIDE THE RIGHT PRACTICES AND CONTEXT

3.1. INTRODUCTION

Having explored multiple facets of how to effectively develop digital-physical products by for example embedding capabilities similar to those of a software company within the manufacturer and by finding the right balance between agility and stability in the product development process, the next question to explore concerns how to implement the needed changes. According to Porter and Heppelmann (2015, p. 114), "*The product and organizational transformations required are difficult and uncertain. The companies and other institutions that can speed this journey will prosper and make a profound difference for society".* With none of the existing digital innovation literature providing operational theory or examples on how to provide the right practices and context, this chapter is guided by the following research objective:

To explore the capability needed to find and implement suitable development practices and a context.

With numerous changes to skills, development, functional and project management practices, and post launch operations, the capability to provide the right practices and context is a significant undertaking in terms of size and complexity. Porter and Heppelmann (2015, p. 98) summarise: "*the nature of smart, connected products substantially changes the work of virtually every function within the manufacturing firm. The core functions—product development, IT, manufacturing, logistics, marketing, sales, and after-sale service—are being redefined, and the intensity of coordination among them is increasing. Entirely new functions are emerging, including those to manage the staggering quantities of data now available. All of this has major implications for the classic organizational structure of manufacturers".* How can a manufacturer build a successful digital value chain? Especially, when typically having to protect, at least to some extent, existing stability-optimised practices.

Based on the successful implementation of several of the needed adjustments within one part of COMP, this chapter provides an example and a model summarizing this implementation to inspire digitalising manufacturers.

3.2. THEORETICAL BACKGROUND

From the literature review (Hendler and Boer, 2019) we know that there is no theory on the capability to implement suitable digital-physical practices and an appropriate context (Finding 9). A few authors relate to the topic and make some suggestions. Svahn et al. (2017, p. 16) describe Volvo Car's journey toward digital innovation. They conclude that this journey "*demonstrates that digital innovation is an organizational capability, not merely a new technological platform or an innovation incubator. Developing digital innovation capability requires fundamentally rethinking how the business is organized, how it makes decisions, with whom it partners, and how those partnerships are managed. These concerns are systematically interrelated and mutually dependent, so companies may find that a failure to address any of these competing concerns may have a wide-ranging impact on the overall success of digital innovation initiatives".* This raises attention for the synergy effects between the changes needed, which requires careful and deliberate design of the change journey.

Another complication, raised by Porter and Heppelmann (2015), concerns the high likelihood that digital-physical product development and delivery capability needs to coexist with the development and delivery of the manufacturer's traditional products. Accordingly, Svahn et al. (2017, p. 116) show with their case study that "*it is possible for established companies to develop digital innovation capabilities while maintaining their core businesses. In fact, it is essential to do so. Successful established companies possess knowledge and expertise that have served them well for years, and the way they have done business is largely institutionalized".* The implication of this dual capability on defining and implementing suitable development practices and a ditto context is suggested by Porter and Heppelmann (2015, p. 112): "*This means that the organizational transformation we are describing will be evolutionary, not revolutionary, and old and new structures will often need to operate in parallel".* Hence, the duality is likely to require an evolutionary change, to be able to protect and exploit existing capabilities effectively. Finally, Porter and Heppelmann (2015, p. 112) suggest: "*Given the scope of the changes, and the scarcity of skills and experience in smart, connected products, many companies will need to pursue hybrid or transitional structures. This will allow scarce talent to be leveraged, experience pooled, and duplication avoided*". Specifically, they suggest to implement the new capabilities via a temporary stand-alone business unit with profit and loss responsibility, via a centre of excellence with key expertise that business units can tap, or via a cross-business-unit steering committee to nurture and coordinate the capability building in a temporary or hybrid structure, which is a complex endeavour, particularly with scarce digital expertise.

Adding to this characterisation of the capability building, Proposition 20 presented in Chapter 2 proposes that if a manufacturer is aiming to digitally enhance a significant portion of its portfolio of physical products, proactive changes to the development context should be initiated before exceptions and their management overload the company's operations, resulting in significantly reduced performance. This adds the dimension of time, i.e. the capability building must be timely in order to not put too much strain on the organisation.

In summary, manufacturers are under pressure to find and implement suitable digital-physical development practices and an appropriate context to be able to adapt their capabilities with the rate of digitalisation of their product portfolios. The literature only sketches the contours of the capability building process that can help a company identify the required changes across the full value chain, create synergy between these changes, and maintain the effective and efficient development and delivery of its traditional products at the same time, all the time. Additionally, the transition needs to be fast enough to enable the company to compete in an ever faster moving market and to avoid exception overload, while taking an evolutionary approach and coping with the scarce digital knowledge available. Thus, to guide manufacturers, this research explores the capability needed to find and implement suitable development practices and ditto context given these four challenges:

1. Scarce digital knowledge
2. Large and complex change with synergy effects and a need for fast digitalisation
3. Need to safeguard existing practices
4. Risk of exception overload

These challenges suggested by the literature are used to help inform the data analysis and derivation of results as described in the next section.

3.3. METHOD

To explore the capability needed for digital-physical product development, the author engaged in one such capability building project in COMP in the role of an agile coach, activity driver and workshop facilitator. Most of the project took place in 2018 and was largely successful. The project was the first coordinated step towards the necessary capability building at COMP.

The first project to benefit from the capability building outcome was Project E, which is described in Hendler (2020). In short, Project E was a digital-physical product development project that started in late 2017. In addition to the core manufactured product components of COMP, it included both internally developed hardware, software and firmware as well as externally developed software in the form of an app. As described in Hendler (2020), the project tested new practices focused on the agile planning and coordination of digital and physical development across a total of fourteen subprocesses. The design of these new agile practices was the outcome of workshops in the capability building initiative, driven by the action researcher, and implemented in project E. Project E also experienced other benefits from the capability building initiative as reported later in this chapter.

The research reported in this chapter combines the case study and the action research method and is based on convenience sampling. It addresses a gap in the research as discovered in Hendler and Boer (2019) and is represented as a construct in the research model (see Figure 4, Chapter 2): *Capability to provide the right practices and context*. This construct is explored by inductively illustrating it with case evidence, while also providing practical examples and operational models for how to provide this capability.

3.3.1. DATA COLLECTION

The data on the capability building process was collected along the action researcher's activities, resulting in meeting notes, pictures of meeting scribbles on whiteboards, notes from informal conversations with initiative participants and Project E participants, solution sketches and notes from workshops. Action research loops in terms of plan, act and fact-find (Lewin, 1946) were conducted as an integrated part of the development and implementation of the new agile practices in Project E, as described in Hendler (2020). Also, meetings were held every two weeks as part of the capability building effort to ensure evaluation of the ongoing efforts and to initiate new actions. Additionally, a large number of documents was collected in the form of plans, emails, formal meeting summaries, formal workshop summaries and power point slides documenting the various solutions and suggestions. Also, calendar entries and meeting descriptions were used as data. The data was triangulated by comparing several sources describing the same events, such as emails, formal meeting summaries and informal conversations with various informants.

With a specific focus on the agile practices implemented in Project E, a survey with five statements using a five-point Likert scale was answered by Project E's team members to measure the perceived short-term effects of the agile coordination practices implemented in Project E (see Hendler (2020) for further details). Furthermore, seven interviews of approx. one hour each were conducted with the various digital-physical project coordinators (Hendler, 2020). This data also provides evidence for the research in this study.

Finally, a year after completion of the capability building initiative, the conclusions were validated in two final interviews with open ended questions: one 60 minute interview with the capability building lead driver and one 30 minute interview with the project manager of Project E.

The questions asked to the project manager and lead driver were:

1. How did you experience the results of the 2018 capability building initiative (in [Project E])?
2. What can we learn from the way we did the initiative? Why do you think the initiative was successful?
3. What has happened during the past year since I left the initiative?
4. What is the current capability building status? Which gaps are still issues?

3.3.2. DATA CAPTURE

The data resulting from the action research on the capability building process was recorded in an action diary as outlined in Appendix D. Observations, contextual changes, reflections and options for future actions were captured in the action researcher's diary (cf. Coghlan and Brannick, 2010), amounting to 50 pages. The interviews were recorded and transcribed by the researcher.

3.3.3. DATA ANALYSIS

The analysis first involved drawing a timeline of the key events in the capability building process and their outcomes based on calendar entries, initiative plans and meeting notes and summaries. Next, data was extracted from all the collected data that offered descriptions of the underlying intentions and assumptions, key decisions and detailed outcomes in terms of performance effects. In accordance with Eisenhardt (1989), understanding the 'why' of what is happening is crucial to internal validity. The extracted data consisted of copied-in 1) observations and 2) reflections from the diary, as well as 3) informant quotes from the interview transcriptions. The extracted data was put into a document to form a consecutive and emerging narrative of the initiative's process, divided into distinct phases: planning, creating recommendations, implementing recommendations, and outcomes, i.e. performance effects. The extracted data fragments were labelled as either 'observation', 'reflection' or 'quote' and with information about the data source to establish a chain of evidence. The analysis objective was to understand how and why the initiative had progressed and what could be learned from it from a management perspective. Next, reading through the extracted data, key data was highlighted and comments were inserted to propose conclusions. The conclusions were iterated by triangulating against various documents and diary notes while keeping the integrity of the informants' quotes.

In accordance with the research model (see Figure 4, Chapter 2), performance is measured in terms of the digital-physical product development performance. Here, the performance of Project E was in focus as this was the first digital-physical project to benefit from the new capabilities implemented. Specifically, the success of the capability building initiative was first measured by evaluating if the problems that were present in a previous digital-physical project and were prioritised as important in order to improve specific performance problems, were now considered resolved or significantly reduced in Project E. The project manager and the initiative lead driver were interviewed, as described above, to assess the extent to which eliminating or reducing these problems had a positive impact on product development performance. The capability building lead driver was accountable for the performance of the business area, which included the performance of Project E, and, therefore, had intimate knowledge of Project E's operations. It should be noted, though, that no objective and direct quantitative measures were available as benchmarks from previous projects to measure the effect of specific capabilities or practices. This means that the assessment of performance effects achieved is subjective and qualitative, albeit well-informed.

In this way, the immediate performance effects as perceived by Project E's team members were analysed when studying the extracted data. With an exploratory and open minded interpretation of performance, these performance effects involved speed of problem solving, coordination effectiveness, higher quality product designs and quality of decision making. These results of the capability building effort were validated in the final two interviews conducted a year after the researcher left the project.

3.3.4. DERIVATION OF RESULTS

Based on the literature review, four topics stood out as challenging when building digital-physical product development capability. Figure 18 shows the three main steps in the empirical analysis, including the four key capability building challenges from the literature: 'Scarce digital knowledge', 'Large and complex change', 'Need to safeguard existing practices' and 'Risk of exception overload' . Iteratively reviewing how COMP started to build the needed capabilities while comparing with the four challenges from the literature resulted in four propositions.

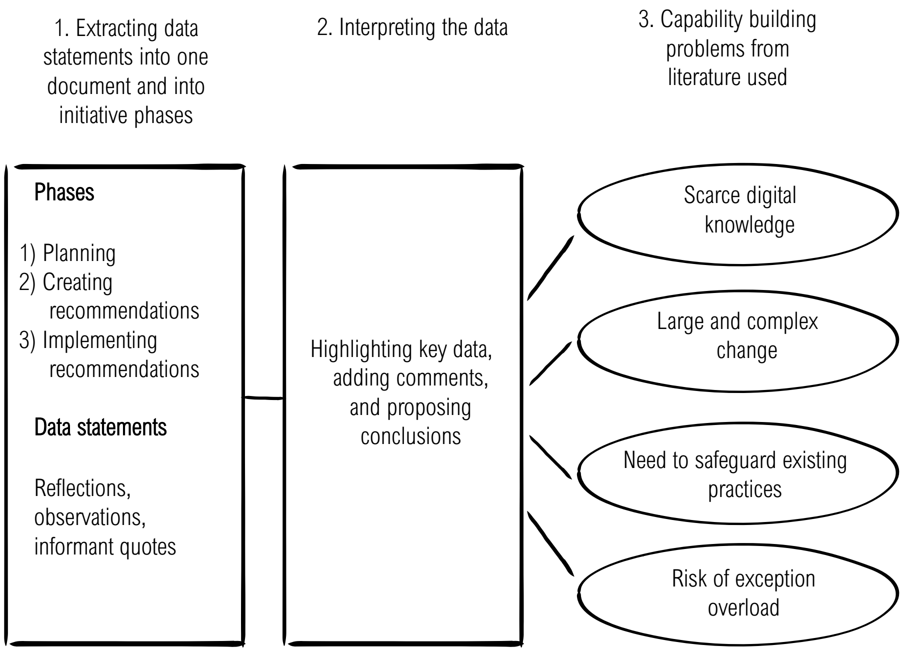

Figure 18 Three steps in the empirical analysis

The case narrative is summarised in the following section. Its conclusions illustrate the research model construct *capability to provide the right practices and context* and its relationship with *product development performance* (see Figure 4, Chapter 2).

3.4. RESULTS

3.4.1. BACKGROUND AND GOAL

In 2017, the product development management set an ambitious vision for a new category of highly complex digital-physical products that were to augment COMP's pure physical products with actuators, sensors and software. The first product development project was underway, Project X. It experienced many problems both in terms of project management with respect to project integration as well as an ill-fitting development context, such as a lack of a supporting operating and financial model, a lack of a digital product and technology strategy, digital platform immaturity and a scarcity and even lack of relevant internal competences. Project X suffered from these problems in terms of e.g. unrealised product features, device compatibility issues, technical problems and dissatisfaction amongst project team members, who were under great pressure to live up to the ambitious, management-set business targets. Particularly, post launch issues were problematic for an organisation not set up to manage this phase in a product's life cycle. Therefore, initially, to be able to deliver on the ambitious vision for a new category of digital-physical products, the product development management decided to set up a workgroup to bring forward a recommendation for how to build the organisational capability needed to succeed in the live phase of digital-physical products.

Following this decision, a cross-functional group met in a workshop to achieve a solid and shared understanding of the problem at hand, and to qualify the commonly heard statement, here from the department head of digital product technology: "*COMP has matured its physical supply chain for many years. Now we need to build up an equally effective digital value chain*". With the right people in the room who had experienced the problems first hand in Project X, the workshop succeeded in building a shared problem description. An eyeopener was the fact that the solution would have to include a large number of new practices, requiring new skills, tools, more people and new processes. Having qualified the statement that COMP was not able to effectively accommodate the development, launch, and live phases of these digital-physical products, the product development management approved the establishment of four workstreams involving people from functional departments critical to establishing digital-physical development, launch and live capability. The functional areas represented in the workstreams included the relatively new digital product technology department, physical product technology, and the physical product development group within this new product category, along with some other functional areas that were trying to adapt to the requirements of digital-physical projects. The four workstreams were set up to focus on the following tasks during 2018, the year ahead:

1. Digital-physical product strategy.
2. Digital-physical business model (money-making logic).
3. Digital-physical operating principles (operating principles and core company competences).
4. Execution (processes, tools, skills, roles, organisation).

All shared the understanding that the four topics, which were inferred from a categorisation model frequently used in COMP, were important to succeed in the long term and that the new capabilities were to be built into, or on top of, the existing organisation to exploit existing capabilities most effectively, as opposed to building a separate business unit.

3.4.2. THE CAPABILITY BUILDING PROCESS

3.4.2.1 Aim and scope

With a great sense of urgency due to a growing pipeline of current and future highly complex digital-physical projects, the workstream focused on 'execution', henceforth labelled Workstream 4, started out with the greatest momentum and accounted for about 90% of the activity related to the new capability building in the year to come. The aim was to be ready with new practices after the summer period to help ongoing projects. At the outset, only one digital-physical product was live in the market (Project X), and the live phase management was exception based, i.e. new practices were implemented to solve the immediate needs with a more or less temporary or product specific intention.

Workstream 4 focused on the execution and live phases, as these phases had proved to be the most challenging. Additionally, the capability building initiative driver, educated by experience, explained: "*the LIVE phase is defined by the choices we make in the* [execution] *phase, therefore, both phases must be in focus now!... An exception based execution creates problems for us.* [Project X] *was allocated the needed resources and was empowered to do what needed to be done. This has meant that we now know a lot about what needs to be done… But we need to build a capability around this work*".

Workstream 4 deferred a number of topics to later efforts, including marketing, sales, front-end process design and a re-organisation. The focus now was on building a digital-physical product development capability for the execution phase and live phase.

3.4.2.2 Creating capability recommendations

In February a successful kick-off workshop was held to clarify the aim and scope of Workstream 4. The workshop benefitted greatly from the continuous and ongoing discussions in the organisation about the constant problem solving that was needed in digital-physical projects as well as the scarcity of the right people skills and resources to address it. The workshop resulted in precisely formulated statements summarizing the problem understanding. In March, a two-day workshop was held with key knowledge holders from relevant projects and departments, including people experienced from pure digital and pure physical areas. The purpose of the workshop was to devise solutions to close the most urgent capability gaps in scope for Workstream 4 from the perspective of the cross-functional group. The workshop plan is summarised in Appendix E, and was addressing the capability gap in the following categories: people, process, technology, governance and collaboration, another categorisation many COMP employees were familiar with.

The workshop was conducted as a two-day agile development project with a shared backlog of prioritised tasks that needed to be addressed. These tasks made up the main part of the agenda and were processed with a scrum board with the columns: to do, doing, done. The 15 workshop participants were split up into teams and processed the tasks one by one in short sprints lasting 20 to 40 minutes, with sprint reviews in plenum following each sprint. In the reviews, the teams gave each other feedback before the next iteration. At the end of the workshop, time was allocated to discuss the maturity and quality of the new recommendations as well as address unaddressed capability gaps. Finally, relevant management joined the workshop to understand and discuss the new capability recommendations for further iterations after the workshop.

The high level tasks addressed in the workshop spanned the topics below, and were considered to be best addressed by a cross-functional team:

- To-be execution process with key tasks, integration points, roles and responsibilities.
- To-be live phase process with key tasks, roles and responsibilities.
- Overview of new roles needed with role descriptions and capacity gap analysis.
- New project collaboration approach ensuring full stack integration.
- Project governance structure and process.
- Digital-physical platform governance structure and process.
- New tools needed.
- Clear accountability of the projects' outcomes including platform and coherence-interests.
- Implementation plan.

The workshop introduction included a presentation and discussion of the shared problem understanding, presentation of Project X and another digital-physical project, Project Y, against which the suggested recommendations were to be tested to ensure their relevance. For effectiveness and efficiency purposes, process definitions and templates were prepared before the workshop to help facilitate the work along with sticky notes with known tasks and key milestones based on the actual schedule of Project X.

The workshop was successful at aligning a cross-functional group and their management towards a large number of recommendations for closing the urgent capability gap. The workshop also benefitted from a pragmatic approach, in which the knowledge in the room would have to suffice so that a 'good' solution, versus the 'best' solution, would be sufficient. Finally, the workshop also functioned as a team-forming kick-off for Workstream 4 as it was two fun days with high energy and great results to be proud of according to the team's own confidence voting at the end of the workshop.

3.4.2.3 Maturing the capability recommendations from the workshop

The many specific and actionable recommendations were matured, partly decentralised by functional experts and, partly cross-functionally to ensure synergies. This work took place over the next six months. The new practices spanned across the following topics:

- Platform, financial and project governance.
- Description of new roles needed by various departments.
- Defining and maturing a digital-physical platform and its operation.
- Plug and play process to help new product development projects exploit the maturing digital-physical platform components.
- Live operations model.
- 'Agile stage-gate' coordination model (as reported in Hendler (2020), Project E).
- New process standard description (as reported in Hendler (2020), Process w/ hw).
- User experience principles and guidelines.
- Capacity planning, budgeting and people hire.
- IT tool selection, integration and implementation.
- Vendor management.
- Full stack quality assurance management.
- Data analytics operations.
- Overall implementation of new capability.

Some of these topics were already being worked on prior to this initiative, but the initiative maintained an important shared problem understanding, and ensured a shared direction and coordination, as well as an identification of new capabilities that had not yet received much attention.

The workstream participants met every 14 days for two hours to, according to the meeting invitation, "*address the cross-functional topics, follow up on tasks and prioritise tasks/ plan towards next meeting. In between meetings we can work in smaller groups on the tasks prioritised and each team member will contribute as workload allows in the given period".* This cadence ensured vital reviews, coordination and alignment on core principles and priorities between key stakeholders, which included department heads and key knowledge holders.

Key inspirations for various recommendations came from knowledge about 'pure digital' areas in the organisation, such as digital marketing material production and corporate IT, and included models for best practice live operations and quality assurance management. Additional inspiration came from other digital-physical projects in other product categories. Finally, many of the recommendations relied on pragmatic problem solving based on Lean principles or by using expert input from the action researcher regarding agile project management, product development and coordination practices.

3.4.2.4 Implementation of the recommendations

The various recommendations were approved by the relevant management and implemented when ready. Generally, the people involved in the newly implemented practices were also involved in their design and felt empowered to do what was necessary. Given the strong relevance of the new practices and roles, they were considered welcome solutions and their implementation happened bottom up without much explanation or explicit considerations about change management aspects such as behavioural design, change willingness and resistance. The implementation efforts were largely unscheduled, i.e. design and implementation happened as fast as possible given the availability of people to do the work. Some recommendations took a long time to implement. For example, finding the resources to hire a data analyst took about a year due to problems determining who in the organisation, i.e. which cost centre, should cover the cost.

In October the workstream hosted a 'social and sharing event', in which all the employees who were envisaged to contribute to the product category's digital-physical projects were invited. Various new practices relevant to the audience were presented. The event included a number of social activities to help establish relationships within the large group of people of around 100 employees. The workstream driver explained: "*we want to paint the full picture of a complex new area for COMP, including building a shared understanding of COMP's overall ambitions and strategy in this area. At the same time we also want, in a fun and engaging way, to put a spotlight on single pieces of the* [new practices] *to start the journey of building specific capabilities in the broader organization working with* [digital-physical] *products across the portfolio, hereunder new ways of working* [in the projects]".

3.4.2.5 The other work streams

The social and sharing event also included an introduction by COMP's product development management to an early strategy for the category's digital-physical products as well as a digital-physical platform strategy (Workstream 1). The business model work (Workstream 2) and operating principles work (Workstream 3), though considered important, had been challenged by not knowing the product category strategy (Workstream 1) and had decided to pause to wait for the output of Workstream 1, which was revealed on this day. Workstream 1 and 2 were also perceived as less urgent, as the executors believed they were able to come up with sufficient case by case problem solutions on the short term. However, some project management hours had been invested in identifying the current operating principles' misfits as part of Workstream 3, and temporary conclusions had been made concerning the importance of the projects to make deliberate and pragmatic choices which, first and foremost, served the projects' interests.

3.4.3. THE RESULTING PERFORMANCE

This initiative was the first coordinated effort across multiple functions in COMP to build digital-physical product development capability. Previous efforts had been smaller, local responses to the immediate needs of digital-physical projects. The new capabilities resulting from this first increment of capability building was evident to Project E, which benefitted from the new capabilities, such as new employees concerned with digital-physical quality assurance, new strengthened user experience principles and competences, a new standardised digital-physical process to help make the initial project planning and communicate hard deadlines to software people, new governance practices, freedom to deselect some standard templates and new agile, trust-based coordination mechanisms to ensure effective ‘full stack’ integration. Project E succeeded with a much better coordination and component integration performance than the previous Project X. The project manager explained: “*I persisted with the new* [agile coordination practices]. *I wanted them to work. They replaced a number of other meetings and the participants kept supporting them”.* Furthermore, digital-physical platform issues were now solved much faster. One battery-related problem that had been unresolved for one and a half years was now solved via the new governance structure in three weeks, due to a clear process and a capable cross-functional decision forum with skilled recommenders. However, due to scarce resources, the governance model did not last long, but the model design and intent continued in a new platform department and is currently being addressed. The few implementation problems, or a lack of speed, concerning the Workstream 4 output, were predominantly caused by a lack of funding or prioritisation due to the extent and speed by which new people were hired into various departments to help build a digital value chain.

No efforts were undertaken to quantifiably measure the effectiveness of the new capabilities, but key problems that were considered to explain previous digital-physical performance problems were now considered solved or reduced by informants. A year later, further efforts had only built upon and strengthened the effect of the capability building efforts in 2018. For instance, new people employed to address digital-physical quality assurance had now turned into a full department. The head of the product category explained when reflecting on the past and future challenges: “*What we did in 2018 helped build our digital-physical capability, but there is much more that needs to be done, especially with our current growth ... building this digital-physical capability is our everyday lives”.* Future areas include business model, operating principles, approaches for determining the technical feasibility of a product concept, marketing, sales strategy, strong product strategies and considerations of how money is spent throughout the life cycle of digital-physical products. Eventually, to avoid exception overload of the organisation, COMP sensitively decided to reduce the ambitious planned growth in terms of the number of new digital-physical product development projects in the portfolio pipeline to a more manageable level of growth. This was announced to allow time to “*complete and mature*” the needed capability.

3.4.4. SO, WHAT DID COMP ACTUALLY DO?

COMP is on a multi-year journey to build its digital-physical product development capability. This first coordinated attempt was focused on a specific category of digital-physical products. The recommendations coming out of the initiative were largely successful. However, most focus was placed on Workstream 4, which was considered the most urgent due to the execution ability. A few recommendations were implemented very late due to the lack of funding prioritised for the expertise needed, such as digital platform engineers to support platform governance, and data analysts. However, the recommendations were rooted in real business needs and were eventually funded, a year later. Other recommendations were highly successful, such as the new agile coordination methods to ensure full-stack integration and new quality assurance expertise that could include digital.

A number of key elements were significant in helping this capability building to succeed. First, the initiative was based on a real need to be able to perform according to management-set project performance targets. Hence, the capability building was based on a problem solving intent and followed a structured problem solving approach:

1. Understand the problem.
2. Structure the problem.
3. Develop solutions.
4. Implement solutions.
5. Monitor for success.

3.4.4.1 *Understand the problem* – through a shared recent experience

The newly formed digital-physical product category area had recently focused all its attention on Project X. This recent experience was processed in a number of formal and informal meetings and had led to the beginning of the coordinated capability building effort and an ability to quickly and precisely summarise a highly multi-faceted problem understanding. In Workstream 4, the level of shared problem understanding was great due to this shared experience, not only amongst the cross-functional workstream participants but also outside this group.

3.4.4.2 *Structure the problem* – into all-encompassing categories

The capability problem was structured into the categories strategy, business model, operating principles and execution. Then, Workstream 4 categorised the problem into the categories: people, process, technology, governance and collaboration (see Figure 1919). This structure allowed an analytical approach to closing the capability gap.

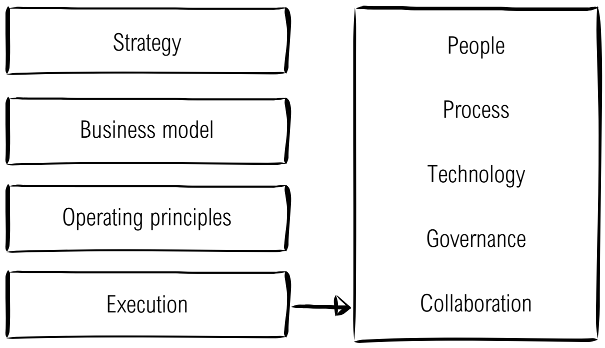

Figure 19 Problem structure

3.4.4.3 *Develop solutions* – cross-functionally and coordinated

The recommendations creation workshop was able to successfully develop highly concrete and actionable recommendations, which the team felt confident about would provide the most important solutions. The solutions were developed by a cross-functional team with knowledge from both the pure digital and pure physical areas, and with a pragmatic approach to find solutions: the goal was not to find the 'best' solutions, but 'good enough', i.e. satisficing (Simon, 1996) solutions, which enabled speedy progress. Outside the workshop, departments initiated various actions to be able to support future projects of the same nature in a similar way. However, the department heads and key people were coordinating with the workstream driver to benefit from synergies and shared learning.

3.4.4.4 *Implement solutions* – via problem bearers

The solutions from Workstream 4 were a response to current problems, and the solution implementers were the ones experiencing the consequence of these problems. Thus, not surprisingly, these highly motivated problem bearers significantly contributed to a largely successful implementation.

3.4.4.5 *Monitor for success* – through established standard business performance measurement

The project category had built the most urgent part of the needed capabilities and continued to mature them in collaboration with the departments in the development context. Pre-existing project and product performance measurements led to a natural monitoring of the capability building, i.e. the problems were solved without formal measurement other than of project and product performance.

3.5. DISCUSSION AND IMPLICATIONS

COMP approached its capability building through action learning. The initial digitalisation strategy did not involve plans for how to build the needed capability. Instead, COMP management responded to the market by initiating digital-physical product development projects and supporting the emergent needs of these projects via resource allocations, prioritisation and exception management. This action learning strategy secured a timely response to the market and a steep learning curve, which COMP managed to exploit.

The pragmatic problem solving approach, taking the perspective of a digital-physical product development project, was considered successful in identifying the most urgent changes for performance optimisation across a large and complex organisation, by exploring and consistently comparing solutions to a recent digital-physical product development project as well as ongoing projects. Coupling this approach with the fact that a cross-functional project group shared recent and problematic digital-physical project experiences, can point towards an important part of the solution towards being able to identify the needed capabilities along a complex value chain. Though a risky approach, not initiating a coordinated capability building effort until after an initial digital-physical product development project has been launched, can result in more efficient and effective capability building in which synergy effects are clearer. Thus, many of the challenges presented by Svahn et al. (2017) and Porter and Heppelmann (2015) regarding size, complexity and synergies are addressed. However, the first ‘pilot’ digital-physical project must be set up to engage with continuous problem solving activities via highly competent and experienced project members and management, who can effectively navigate established company practices as well as exploit available slack.

Porter and Heppelmann (2015) and Svahn et al. (2017) both describe the need to maintain the existing capability to develop and deliver traditionally manufactured, i.e. physical-only products. Accordingly, the pragmatic problem solving approach was successful regarding the ambition to integrate the newly needed capabilities into the existing product development capability while respecting the existing stability-optimised practices. This approach was also enabled by the fact that a re-organisation of departments and people was out of scope. Hence, newly hired experts were integrated into existing structures. Unsatisfactory performance gave way to a pragmatic, bottom-up, problem-solving approach. Had COMP decided to build a separate business unit, a more vision and plan-driven approach in which COMP sought inspiration from tech companies might have been more successful to guide people and the development of new practices and structures.

Finally, the coordinated capability effort was considered late, but maybe not too late. COMP was already experiencing the taxing effects on the project members and the development context of established processes and supporting departments. However, the coordinated capability building effort was just in time to avoid significant exception overload (Proposition 20). The selected time resulted in a clear and crisp problem understanding while being conducive to mitigating the most detrimental product performance effects of the live phase of Project X.

The propositions below summarise key elements to be able to tackle the size and complexities related to the identification and implementation of the needed capabilities for digital-physical product development. The propositions are based on the following assumptions:

- The existing product development capability must be sustained, but expanded with the capability to develop and operate digital-physical products.
- The competitive situation allows a gradual growth of the share of digital-physical projects in the project portfolio.
- A re-organisation is only relevant to remove impediments, and may come later.

Proposition 21: Manufacturing companies can effectively ensure sufficient knowledge to build digital-physical product development capability by:

- Executing an initial well-staffed and well-resourced digital-physical project with realistic performance targets.
- Developing and testing new practices in that project.
- Implementing the new practices in current digital-physical projects, and learning about their effectiveness by comparing the experiences obtained in the pilot and the current digital-physical product development projects.

Proposition 22: Manufacturing companies can effectively and efficiently manage the large and complex change required to build digital-physical product development capability by:

- Establishing and empowering a cross-functional team experienced with digital-physical product development and representing key parts of the product development value chain.
- Focusing on the most urgent capability building to be able to deliver current digital-physical project(s) with acceptable performance.
- Completing and maturing the needed capability in subsequent implementation waves.

Proposition 23: Manufacturing companies can effectively identify and implement the required digital-physical capability without disrupting existing stability-optimised practices by:

- (Initially) refraining from a re-organisation of the company, and, rather, implementing new capabilities, to the extent possible, by complementing the existing capabilities within existing structures.

Proposition 24: Digitalising manufacturing companies can avoid exception overload as a result of engaging with digital-physical product development by:

- Implementing required capabilities before a significant growth in the number of digital-physical projects.
- Not growing the digital-physical product portfolio faster than the organisation can support.

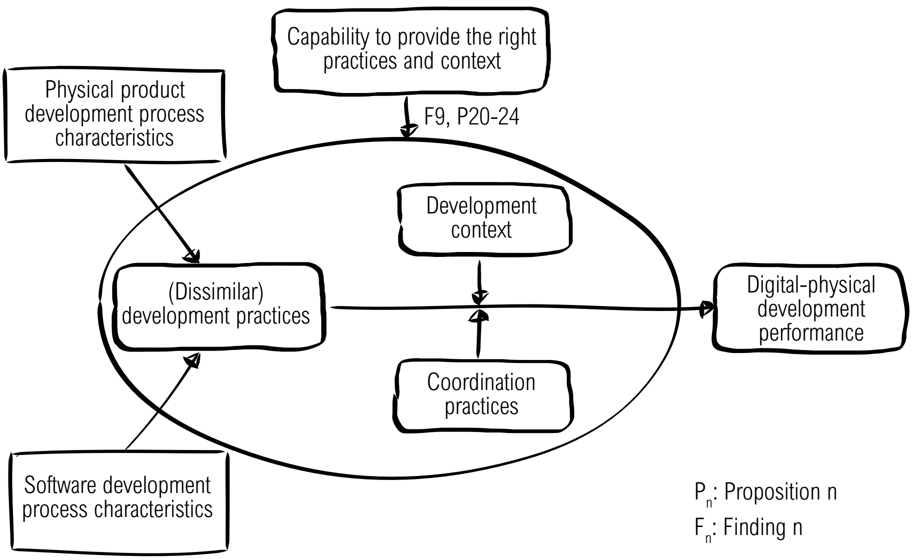

Figure 20 The research model updated with the propositions describing the capability construct and its relationship with performance

Figure 20 depicts the research model with all the research findings and propositions relevant to the construct: Capability to provide the right practices and context. Finding 9 (Hendler and Boer, 2019) describes the lack of theory and Proposition 20 (Chapter 2) adds the importance of building the needed capabilities in a timely manner to avoid exception overload.

The approach described by Propositions 21-24 has demonstrated success in the early capability building of a manufacturer, in which a smaller percentage of the product portfolio was sought digitalised. Other approaches should be considered in industries where digitalisation is projected to completely disrupt the viability of the manufacturer’s traditional products within a few years, or in industries where a much steeper growth is expected from digital-physical products. More in-depth case study research is needed to describe and categorise different capability building processes as outlined by Christensen (2006).

Figure 21 depicts key points of COMP’s implementation approach.

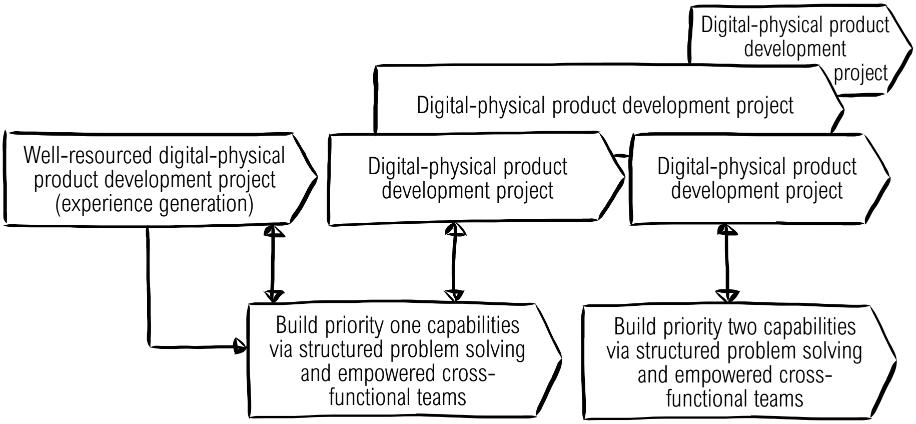

Figure 21 COMP's capability building approach

3.6. CONCLUSION

This chapter has explored the capability needed to find and implement suitable development practices and a context for digital-physical product development within a manufacturing company. Using a combined case study and action research method, four propositions have been formulated to describe this capability and to further illustrate the research model. The evidence is based on a successful capability building example within one company. The research demonstrates a capability building approach that accommodates a gradual increase in the number of digital-physical product development projects. This involves that an initial, well resourced, digital-physical product development project is kicked-off to establish shared experience with the capabilities needed for subsequent projects. Subsequent projects benefit from a coordinated and well-informed capability building and capacity expansion of available expertise. Thus, this approach avoids exception overload of the supporting development context. However, it involves a high risk relating to the performance of the first project. Furthermore, the study shows the effectiveness of a pragmatic and structured problem-solving approach performed by an empowered, cross-functional group toward closing a number of well-defined capability gaps while embedding the new capabilities into the existing, more stability-optimised, structures and practices. This was done by refraining from a more radical reorganisation and, rather, focusing on digital-physical product development projects and their needs as the units of analysis. More research is needed to describe and categorise different capability building efforts in a variety of company and market contexts.

CHAPTER 4. CONCLUSION

This concluding chapter summarises the main results reported in this thesis. It first addresses the thesis research objective with a discussion that relates the research results to the literature that has been used as a lens to help develop the tentative theory. Second, it explicates the contributions to theory and lists an overview of the findings and propositions developed in this research. Third, it gives specific recommendations to practitioners.

4.1. DISCUSSION

With a starting point in a relevant and significant problem for manufacturing companies, this research provides some tentative and relatable theory to fulfil the objective:

To explore how to effectively develop digital-physical products.

Operationalizing this objective, the research has been structured around three research areas: development practices and context, coordination practices and capability building. Below, the research objective is answered by addressing each area posed as a question and relating the answer to the literature.

4.1.1. WHICH PRACTICES AND CONTEXT EFFECTIVELY SUPPORT THE CHARACTERISTICS OF THE DIGITAL-PHYSICAL PRODUCT DEVELOPMENT PROCESS?

As described in Hendler and Boer (2019), Finding 2, the research proposes that "*[d]igital-physical product development predominantly involves separate and different digital and physical development practices and organisations*". This finding is based on case studies such as Joglekar and Rosenthal (2003), Broy (2005), Broy et al. (2007), Woodward and Mosterman (2007), Cordeiro et al. (2008), Katumba and Knauss (2014), Lerch and Gotsch (2015) and Lwakatare et al. (2016). The differences between these separate subprocesses can be expressed in terms of their process characteristics and materiality (e.g. Karlsson and Lovén, 2005; Andreasson and Henfridsson, 2008; Yoo et al., 2010; Svahn and Henfridsson, 2012; Katumba and Knauss, 2014; Svahn et al., 2017; Dawid et al., 2017, Eklund and Berger, 2017). Hendler and Boer (2019, Finding 3) propose that "*digital development is optimised for adaptability via fast feature delivery, effective exploration and fast adaptation using agile development methods with late*" and, as established in Hendler (2020), gradual binding (e.g. Schwaber and Beedle, 2001; Cohn, 2010; Svahn, 2012; Svahn and Henfridsson, 2012; Eklund and Bosch, 2012; Eklund et al., 2014; Lwakatare et al., 2016; Cooper, 2016; Könnölä et al., 2016; Eklund and Berger, 2017). Hendler and Boer (2019, Finding 3) also proposes that physical development is optimised for stability via "*efficient component development, stable exploitation of existing investments, manufacturability and unit cost*" optimisation, and "*long lead time processes*" using a linear and "*firm-centric development process with early binding*" (e.g. Svahn, 2012; Svahn and Henfridsson, 2012; Cooper, 2016). Combining these processes in digital-physical product development renders a process that "*is characterised by a mixed materiality and a high degree of complexity, diversity, interdependence and uncertainty*" as described in Hendler and Boer (2019), Finding 1 (e.g., Fornaciari and Sciuto, 1999; Broy, 2005; Rottman, 2006; Broy et al., 2007; Woodward and Mosterman, 2007; Andreasson and Henfridsson, 2008; Yoo et al., 2010; Svahn and Henfridsson, 2012; Eklund et al., 2014; Katumba and Knauss, 2014; Dawid et al., 2017; Eklund and Berger, 2017; Svahn et al., 2017;), "*which requires manufacturers to rethink existing, and develop new, product development practices*" (Hendler and Boer (2019), Finding 1) (e.g. Broy, 2005; Yoo et al., 2010; Lee and Berente, 2012; Yoo et al., 2012; Porter and Heppelmann, 2015; Svahn et al., 2015; Abrell et al., 2016; Eklund and Berger, 2017). However, the differences between digital and physical development complicate successful combination (e.g. Karlström and Runeson, 2006; Diegel et al., 2008; Evans, 2009; Eklund and Bosch, 2012; Eklund et al., 2014 Eklund and Berger, 2017). As a principle finding, the research finds that when a company combines the stability-optimised physical product development process with the adaptability-optimised digital development process, performance trade-offs must be made: "*Either the former* [process] *must become more adaptable, the latter must become less adaptable or both need to change, which may reduce the performance of one or both subprocesses but should lead to optimal performance of the overall process*" (Hendler (2019), Proposition 7). This relates to the idea of Reinertsen (2009) who describes the importance of making good economic trade-offs throughout a product's lifecycle.

Specifically, with "*high interdependency between digital and physical product development, imposing the early binding typical of physical development* [on digital development] *is limiting the subsequent exploitation of new knowledge in digital development"* (Hendler (2019), Proposition 3) (e.g. Karlström and Runeson, 2006; Eklund and Bosch, 2012; Eklund and Berger, 2017). Hence, imposing early binding reduces the adaptability of the digital development process and, potentially, the value of the resulting digital-physical product. Nevertheless, decreased digital adaptability will not necessarily always lead to a significant product quality decrease. Finally, digital-physical process combination entails that the physical product development process experiences high levels of exception management (Hendler (2019), Proposition 6), unless it, and its context, changes and becomes more adaptable.

Importantly, the COMP case demonstrates that it is feasible for both digital and physical to adapt to each other's development practices, albeit it only to a certain extent (e.g. Lenfle and Loch, 2010; Conforto et al., 2014; Cooper, 2014; Heeager et al., 2016; Vedsmand et al., 2016). Specifically, to optimise the performance of digital-physical product development it seems feasible to implement agile practices to increase the adaptability of physical product development 1) in the most uncertain subprocesses during high levels of uncertainty, that is, in the phases prior to the Bill of Materials lock, when the need for team learning is greatest, 2) in the project management team, for that team to be able to effectively respond to the project's high uncertainty and complexity, and 3) in the project's coordination and planning mechanisms, to enable transparency and cross-functional mutual adjustment to exploit available schedule and resource slack, and resource prioritisation options, throughout the project's life. At the same time, it is feasible for the digital development process to adapt to the physical development process by front-loading key digital-physical interdependent design decisions. Furthermore, when a manufacturer engages a digital vendor with digital development before the physical product design is locked, it requires the physical product development to accommodate some very early and incremental binding of its product design. In summary, implementing agile practices in physical product development is feasible to the extent it allows adherence to high cost of delay deadlines, including early physical binding to avoid significantly compromising project performance.

Concurrent projects in highly optimised operations may be impacted when a manufacturer is engaging with the less stable digital-physical product development, as the operations of supporting departments as well as manufacturing efficiencies may be significantly interrupted. The reason for such interruptions in the development context is exception management overload. This overload is a result of changes in, for example, business models, marketing operations, post launch operations, quality acceptance criteria, product platforms, digital tools, purchasing practices and competences for project governance, support functions and company strategy (Hendler, 2019). If such changes are not expected, as in the case of COMP in their first digital-physical projects, they require engaging additional resources, unforeseen, from development projects going on at the same time, which goes at the expense of the performance of these projects. In order to prevent this situation, exception overload and resource cannibalisation, proactive and, essentially, preventative changes to the development context should be initiated.

Finally, digital-physical development also requires changes in product development practices (Joglekar and Rosenthal, 2003; Kettunen, 2003; Broy, 2005; Karlsson and Lovén, 2005; Karlström and Runeson, 2006; Broy et al., 2007; Andreasson and Henfridsson, 2008; Yoo et al., 2010, 2012; Svahn and Henfridsson, 2012; Katumba and Knauss, 2014; Porter and Heppelmann, 2014; Porter and Heppelmann, 2015; Svahn et al., 2015; Dawid et al., 2017), including rethinking marketing strategies, organizing the project to include digital competences, developing new testing methods, becoming more externally oriented and focusing on new product architectures (Hendler (2019), Proposition 11).

4.1.2. WHICH PRACTICES EFFECTIVELY COORDINATE DIGITAL-PHYSICAL PRODUCT DEVELOPMENT?

Digital and physical product development tend to use different coordination practices (e.g. Boehm and Turner, 2004; Svahn and Henfridsson, 2012). However, the literature is immature concerning which coordination practices to use when combining the two (Svahn, 2012; Nambisan et al., 2017; Holmström, 2018). COMP has traditionally, and predominantly, relied on coordination through standardisation of skills (roles and responsibilities), process (schedule and integration points) and output (deliverables). Digital development departments and companies tend to rely on teams, empowerment, transparency and frequent, cadenced meetings (e.g. Kniberg, 2015; Sutherland, 2015; Larman and Vodde, 2016; Knaster and Leffingwell, 2017; Schwaber and Sutherland, 2017), all of which support coordination through mutual adjustment.

As proposed in Hendler (2020), coordination practices suitable for combining digital and physical product development need to, in particular, accommodate the challenging, combined process characteristics in terms of high interdependency, diversity and uncertainty as well as differences in the duration of the development cycles, language, mindsets and planning practices (e.g. stories vs. man-hours) and late versus early binding. The coordination practices need to be able to accommodate the negotiation of stability-adaptability performance trade-offs through the facilitation of ongoing cross-functional learning about processes, content and mindsets (Hendler (2020), Proposition 16).

Given these conditions, Hendler (2020, Appendix C, p. 259) uses inspiration from Mintzberg (1979) and finds that "*effective digital-physical coordination involves* [both] *standardization of process, output and skills to accommodate the stability needed for efficient physical product development*" and agile coordination practices (e.g. Kniberg, 2015; Sutherland, 2015; Larman and Vodde, 2016; Knaster and Leffingwell, 2017; Schwaber and Sutherland, 2017) to accommodate adaptability. The standardisation of skills, process and output in the form of process documentation enables better informed stability-adaptability trade-off decision-making (Hendler (2020), Proposition 14), in that the stability compromises become visible and easy to communicate. Furthermore, according to Hendler (2020, Proposition 15), standardizing an overall meta-process of cadenced, agile coordination events, such as scrum events (Sutherland, 2015) and a version of PI planning from the Scaled Agile Framework (Knaster and Leffingwell, 2017), and combining this standardisation with individuals who are both informed and empowered, facilitates and results in mutual adjustment (Mintzberg, 1979). This allows decisions, which trade off stability with adaptability, and vice versa, across both agile and non-agile subprocesses to be better informed. Frequent mutual adjustment allows adaptability, effective communication, a shared language, and understanding of each other's constraints and motivations.

Thus, the differences between digital and physical product development can be negotiated continuously and effectively via a version of a hybrid stability-adaptability development model (e.g. Cooper, 2016; Vedsmand et al., 2016; Cooper and Sommer, 2018) described, and shown in Figures 11 and 15, in Chapter 2.

4.1.3. HOW TO EFFECTIVELY PROVIDE THE CAPABILITY TO FIND AND IMPLEMENT SUITABLE PRACTICES AND A DEVELOPMENT CONTEXT?

With no available theory on how to provide the right capability to find and implement suitable practices and a context, this research finds evidence for an effective way of doing so. The specific challenge of the field of digital-physical product development is that manufacturers are under pressure to adapt their capabilities with the rate of digitalisation of their product portfolios, which may be very fast (Porter and Heppelmann, 2015). The literature outlines a capability building process that must be able to identify needed changes across the full value chain (Porter and Heppelmann, 2015), implement them with respect to the synergy effects between these changes (Svahn et al., 2017), and maintain lucrative and stable development and delivery of its traditional, i.e. physical, products (Porter and Heppelmann, 2015; Svahn et al., 2017). This capability building needs to be fast enough for the manufacturer to be able to compete, while avoiding an exception overload of the supporting development context and adapting to a reality with scarce digital resources, by taking an evolutionary approach at the same time (Porter and Heppelmann, 2015).

Addressing these challenges, this research demonstrates an effective model. The model involves that an initial digital-physical project is executed to collect learning about the capability the organisation needs to build and where to start. This requires that the initial project is well staffed and resourced to enable ongoing problem solving and learning, and that performance targets are set realistically. With the experience from this project, an effective and coordinated capability building effort can be initiated by empowering a cross-functional team with the relevant experience from inside the pilot project as well as from supporting functions. The experienced team is effectively able to identify the capability gaps and prioritise the most urgent ones for the first capability building wave. This coordinated effort can follow the steps of a structured problem solving process, in order to address specific problems hindering performance and pragmatically implement solutions as soon as the opportunity is there and the resources are available. This work can take place while both supporting but also learning from ongoing projects to test solutions and help the next digital-physical projects to succeed, projects in which the capability building team members are working themselves. In this way, a manufacturer can gradually increase the percentage of digital-physical projects in the project portfolio to adapt to scarce but maturing digital and digital-physical capabilities and capacities. Subsequently, additional capability building waves can continue an ongoing maturation of the needed capability. Importantly, with a more bottom-up approach, a re-organisation is not in scope and new capabilities are implemented into existing structures to add to the existing capabilities. Also, in the interest of efficiency and effectiveness, the ambition is to find and implement 'good enough' practices that solve the problems, not necessarily 'best' practices (Simon, 1996).

4.2. CONTRIBUTIONS TO THEORY

This research establishes that the phenomenon, digital-physical product development, both exist and is a relevant topic to companies that manufacture physical products. Hendler and Boer (2019) show that, unfortunately, research on the development of digital-physical products, particularly from a manufacturer's viewpoint, is in the beginning of descriptive theory building (Christensen, 2006). This means that researchers mostly observe, describe and measure the phenomenon from various viewpoints (Hendler and Boer, 2019). The literature "*is emerging but the set of topics addressed is highly scattered and incomplete. There is no coherent body of theory*" (Hendler and Boer (2019), Finding 9). Thus, the literature does not offer an operational or a coherent body of theory on a context that can effectively support digital-physical product development, on how to develop digital-physical products effectively, or on the capability to find and implement the right practices (Hendler and Boer (2019), Finding 9). Building on this body of literature, this PhD is instrumental for research concerning how to effectively develop digital-physical products by providing tentative descriptive theory in the form of a research model with findings and propositions.

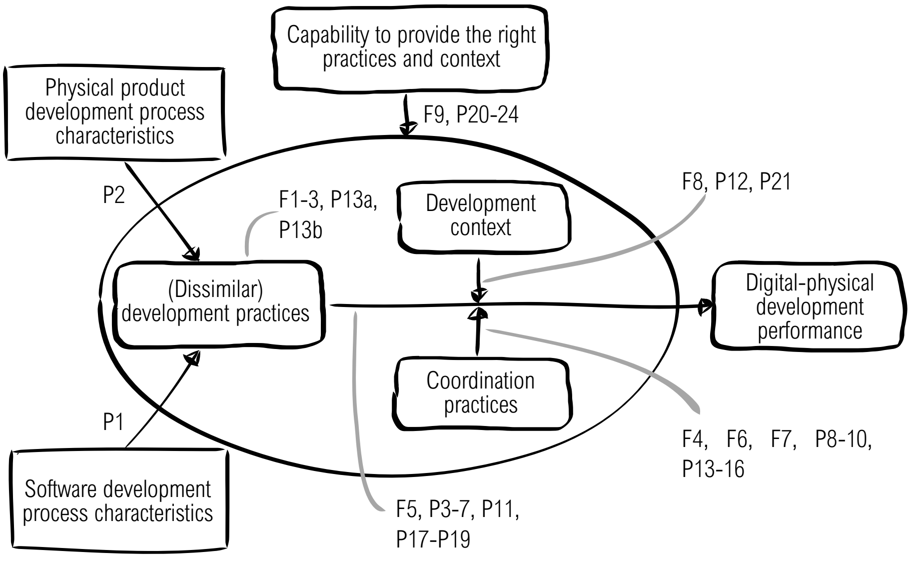

Figure 22 The research model (see Figure 4) with all findings and propositions.

The research model includes a set of *development practices* consisting of the combined, but separately executed and largely *dissimilar* digital and physical product development subprocesses and their *characteristics*. See Figure 14 in Chapter 2 for a model that elaborates on the dissimilar development processes and their characteristics. The two processes can be combined using *coordination practices*. This combination is challenged by the dissimilarities between the digital and physical development practices. Importantly, the coordination practices moderate the relationship "*between the dissimilar development practices and the overall digital-physical development performance" (Hendler and Boer (2019), Appendix A, p. 180)*. See Figure 6 in Hendler (2020), Appendix C, for a model that elaborates on the coordination practices and their relationship with performance. The *development context* moderates the relationship between the development practices and their performance.

The research model established in Hendler and Boer (2019) delineates three critical areas for research, which pose new innovation management challenges concerning how to coordinate digital-physical product development (area 1), how to fit digital-physical product development practices and their context to the process characteristics and the differences in materials (area 2), and how to find and implement the right practices and context (area 3).

Within the three research areas, this PhD contributes with 9 findings (based on the literature review in Hendler and Boer (2019)) and 24 propositions (based on case study evidence reported in Hendler (2019) and Hendler (2020), and Chapters 2 and 3 in this thesis document). In Figure 22 these are linked to the various constructs and relationships in the research model. To provide an overview of this theoretical contribution, the next subsections include the findings and propositions organised according to the three research areas.

Together, the research model with constructs and relationships, the three research areas, the findings and the propositions with accompanying explanations and domain descriptions describe the contribution to, and provide a platform for further research into, digital-physical product development theory.

4.2.1. EFFECTIVE COORDINATION PRACTICES

Finding 4: "*Differences between digital and physical development complicate successful combination and it is often the software development practices that adapts to the requirements of the physical development practices*" (Hendler and Boer, 2019).

Finding 6: "*Some literature advocates making the physical product development practices more agile. However, there is a scarcity of literature investigating this possibility or proposing other mechanisms to combine or reconcile the two processes, and their effects on the overall process*" (Hendler and Boer, 2019).

Finding 7: "*Literature does not provide clear guidelines for balancing the levels of integration and differentiation between software and physical product development in a digital-physical product development process*" (Hendler and Boer, 2019).

Proposition 8: *"If digital and physical collaborate towards early physical binding, digital development is more likely to be able to successfully adapt to the early binding and design constraint from the physical product development process"* (Hendler, 2019).

Proposition 9: *"To avoid faulty assumptions and, thus, ineffectiveness, digital-physical product development can benefit significantly from ensuring cross-functionality, good collaboration skills, a shared language, and understanding of schedule and design constraints, the cost of delay, the impact of uncertainty and the cost of change associated with that"* (Hendler, 2019).

Proposition 10: *"In order to achieve a performance gain from combining the digital and the physical product development processes, managing the trade-offs between these processes requires close collaboration and effective communication"* (Hendler, 2019).

Proposition 13a(1a): *"The agility-optimised digital and stability-optimised physical development processes deploy different development cycle lengths (e.g. late versus early binding), planning practices (e.g. stories vs. man-hours), language and mindsets"* (Hendler, 2020).

Proposition 13b(1b): *"The uncertainty, diversity and interdependency of the combined digital-physical development process are higher than those of the individual processes"* (Hendler, 2020).

Proposition 13c(1c): *"The association between the combined digital-physical process and the performance of that process is moderated by the practices deployed to coordinate the digital and physical development subprocesses"* (Hendler, 2020).

Proposition 14(2): *"Coordination through standardisation of process (e.g. integration points), output (deliverables) and skills (roles, responsibilities) enables better informed stability-adaptability trade-off decision-making which, in turn, moderates the association between the combined digital-physical process and its performance"* (Hendler, 2020).

Proposition 15(3): *"Coordination through standardisation of process in the form of a standardised meta-process of cadenced coordination events, combined with empowered and informed individuals, facilitates mutual adjustment, which enables better informed stability-adaptability trade-off decision-making"* (Hendler, 2020).

Proposition 16(4): *"Effectively coordinating digital-physical product development involves facilitating ongoing cross-functional learning about processes, content and mindsets, and adapting coordination practices accordingly"* (Hendler, 2020).

4.2.2. SUITABLE PRACTICES AND A CONTEXT THAT FIT THE PROCESS CHARACTERISTICS

Finding 1: "*Digital-physical product development is characterised by a mixed materiality and a high degree of complexity, diversity, interdependence and uncertainty, which requires manufacturers to rethink existing, and develop new, product development practices*" (Hendler and Boer, 2019).

Finding 2: "*Digital-physical product development predominantly involves separate and different digital and physical development practices and organisations*" (Hendler and Boer, 2019).

Finding 3: "*Physical and digital development deploy significantly different practices that are predominantly explained by differences in uncertainty, materiality and product architecture. Digital development is optimised for fast feature delivery, effective exploration and fast adaptation using agile development methods with late binding. Physical development is optimised for efficient component development, stable exploitation of existing investments, manufacturability and unit cost while coping with long lead time processes using a firm-centric, linear development process with early binding*" (Hendler and Boer, 2019).

Finding 5: "*Despite differences in practices complicating their successful combination, some authors observe that the digital immateriality and development practices complement the physical product development practices by mitigating some uncertainty*" (Hendler and Boer, 2019).

Finding 8: "*The literature suggests that the product development context within a traditional manufacturer, including its strategy, organisational arrangements, culture, processes outside the product development function, and its business model, is not able to successfully support, and needs to be adapted to, the requirements of digital-physical product development. However, although several bits and pieces have been proposed, only little operational insight exists into the changes required*" (Hendler and Boer, 2019).

Proposition 1: *"Compared to physical product development, the digital development process is characterised by a higher degree of uncertainty, a lower degree of diversity and digital immateriality, which allows for an adaptability-optimised development process of short, iterative development cycles with predominantly cross-functional teams, empowered decision-making, one product vision holder, a floating scope, short* *development cycles, late binding, short up-front planning, and several releases per product"* (Hendler, 2019).

Proposition 2: *"Compared to digital development, the physical product development process is characterised by a lower degree of uncertainty, a higher degree of diversity and a physical materiality, which allows for a stability-optimised development process of one long development cycle with a large extent of functional unit grouping, hierarchical and consensus driven decision-making, multiple product vision holders, a highly formalised and high-level, schedule-bound development process, early binding, extensive up-front planning, and one launch per product"* (Hendler, 2019).

Proposition 3: *"With high interdependency between digital and physical product development, imposing the early binding typical of physical development is limiting the subsequent exploitation of new knowledge in digital development, hence, reducing the digital adaptability and the potential value of the digital-physical product"* (Hendler, 2019).

Proposition 4: *"Digital development can adapt easier to the requirements of the physical development process as well as absorb some of its undesired variability, without causing a significant quality decrease of the product"* (Hendler, 2019).

Proposition 5: *"Supporting and even accommodating more agility in digital development (if not already fully adaptability-optimised) helps software development to adapt to the increased uncertainty from combining with physical product development"* (Hendler, 2019).

Proposition 6: "*In case of a high degree of interdependence, the physical product development process is bound to experience high levels of exception management and can benefit from building more flexibility into the process, including later binding and slack, to accommodate the added uncertainty from the digital development process"* (Hendler, 2019).

Proposition 7: "*When combining a physical stability-optimised product development process and a digital adaptability-optimised development process, either the former must become more adaptable, the latter must become less adaptable or both need to change, which may reduce the performance of one or both subprocesses but should lead to optimal performance of the overall process"* (Hendler, 2019).

Proposition 11: *"Compared to traditional physical product development, digital-physical development is likely to involve a higher degree of uncertainty, interdependence, complexity and diversity that, coupled with the digital materiality, requires changes in product development practices, including rethinking marketing strategies, becoming more externally oriented, developing new testing methods, organizing the project to include digital competences at all levels, and focusing on product architecture and dependency mapping"* (Hendler, 2019).

Proposition 12: *"Compared to traditional physical product development, digital-physical development is likely to involve a higher degree of uncertainty, interdependence, complexity and diversity that, coupled with the digital immateriality, requires changes in the development context, including business model innovation, rethinking marketing operations, establishing post launch operations and new digital quality acceptance criteria, rethinking product platform(s), investing in digital tools, and ensuring digital competences for project governance and support functions including marketing, business model development and purchasing"* (Hendler, 2019).

Proposition 17: To optimise the performance of digital-physical product development agile practices, to increase the adaptability of physical product development, are beneficial:

- In the most uncertain subprocesses during high levels of uncertainty towards hard deadlines such as the Bill of Materials lock when the need for team learning is great.
- In the project's management team to be able to appropriately respond to the project's high degree of uncertainty.
- In the project's coordination and planning mechanisms to enable transparency and cross-functional mutual adjustment to exploit available schedule and resource slack, and resource prioritisation options, throughout the project's life.

Proposition 18: To optimise the performance of the digital-physical product development process in which digital development starts *before* the physical product design binding, the physical product development needs to implement some incremental binding of the product design earlier than the product binding in purely physical product development projects.

Proposition 19: To optimise the overall digital-physical product development process, implementing agile practices in physical product development is feasible to the extent that high cost of delay deadlines, including the early physical binding, are met so as to avoid significantly compromising the project's own performance, and that of concurrent projects.

4.2.3. THE CAPABILITY TO FIND AND IMPLEMENT THESE PRACTICES AND CONTEXT

Finding 9: "*Literature on digital-physical product development is emerging but the set of topics addressed is highly scattered and incomplete. There is no coherent body of theory on 1) the practices and context required to effectively combine digital and physical product development and 2) the capability to find and, then, implement these practices and their context effectively"* (Hendler and Boer, 2019).

Proposition 20: If a manufacturer is aiming to digitally enhance a significant portion of its portfolio of physical products, proactive changes to the development context should be initiated before a potential exception management overload of the company's operations results in significantly reduced performance.

Proposition 21: Manufacturing companies can effectively ensure sufficient knowledge to build digital-physical product development capability by:

- Executing an initial well-staffed and well-resourced digital-physical project with realistic performance targets.
- Developing and testing new practices in that project.
- Implementing the new practices in current digital-physical projects, and learning about their effectiveness by comparing the experiences obtained in the pilot and the current digital-physical product development projects.

Proposition 22: Manufacturing companies can effectively and efficiently manage the large and complex change required to build digital-physical product development capability by:

- Establishing and empowering a cross-functional team experienced with digital-physical product development and representing key parts of the product development value chain.
- Focusing on the most urgent capability building to be able to deliver current digital-physical project(s) with acceptable performance.
- Completing and maturing the needed capability in subsequent implementation waves.

Proposition 23: Manufacturing companies can effectively identify and implement the required digital-physical capability without disrupting existing stability-optimised practices by:

- (Initially) refraining from a re-organisation of the company, and, rather, implementing new capabilities, to the extent possible, by complementing the existing capabilities within existing structures.

Proposition 24: Digitalising manufacturing companies can avoid exception overload as a result of engaging with digital-physical product development by:

- Implementing required capabilities before a significant growth in the number of digital-physical projects.
- Not growing the digital-physical product portfolio faster than the organisation can support.

4.3. CONTRIBUTIONS TO PRACTICE

While keeping the case company's identity disguised, this research has sought to present as much detail and contextual data as possible to enable practitioners to relate to the resulting propositions and be able to extract relevant practices from the case examples. Additionally, this research has sought to provide sufficient explanations to enable practitioners to relate to in a way that equips them to customise their own practices.

Below, key information and recommendations for practitioners are listed. These initially include a foundational understanding to be able to make decisions regarding digital-physical product development. Also, specific practices or descriptions from the COMP example are highlighted which may call for action within a digitalising manufacturer who has relatively little experience with digital development in its product development.

4.3.1. FOUNDATIONAL UNDERSTANDING

- Engaging with digital-physical product development involves engaging with a new innovation management discipline which requires *significant changes* to a manufacturers value chain. This includes development practices and their context such as the skills and processes of supporting departments, for example, platform management, business modelling, and marketing. Such significant changes are necessary whether the manufacturer is insourcing or outsourcing its software development. Therefore, engaging with digital-physical development requires a significant, multi-year capability building effort.
- Digital-physical product development involves combining physical product development with software development. The digital and physical subprocesses have significant, conflicting differences which means that their combination will have some detrimental consequences on either or both of the subprocesses. These detrimental consequences can be accepted *deliberately* together with their effects on the performance of the combined digital-physical product development process, or tackled to reduce or even avoid negative performance effects.
- The primary reason for the combination having a detrimental effect relates to the timing of binding product decisions. Physical development needs early binding to be able to communicate a locked Bill of Materials to production. Digital has a gradual binding with final design decisions made weeks or days before a release. With digital-physical interdependent design decisions, the physical binding must adapt to digital, or vice versa, at least to some extent.
- Three, not mutually exclusive, strategies should be considered when combining digital and physical product development (Hendler (2019), Appendix B, p. 216):
    - “[Adapting one] *or both of the subprocesses to the other.*
    - *Effective coordination between the two subprocesses.*
    - *Implementation of new development practices and a suitable development context.*”

  In the case of COMP, all three strategies contributed to successful digital-physical product development.

- A key challenge is to find solutions that allow a manufacturer to preserve its ability to *stably* and efficiently develop and manufacture purely physical products *while* becoming more *adaptable* to accommodate the digital-physical product development and new market dynamics.
- Traditionally, digital tends to adapt to physical product development in e.g. electronics products, i.e. software development has typically adapted to a stage-gate model with a waterfall approach. This research demonstrates the feasibility of physical product development also adapting to digital development by implementing agile practices, albeit only to the extent to which the Bill of Materials and other information to production is not significantly delayed due to the excessively high costs of delay. That is, both physical and digital adapts to each other in order to optimise the performance of the overall digital-physical product development performance

4.3.2. SUITABLE DEVELOPMENT PRACTICES AND A CONTEXT THAT FIT THE PROCESS CHARACTERISTICS

- Project practices need to adapt to the mixed materiality, such as designing for big data and life after launch. Adapting to the increased levels of uncertainty, complexity, diversity and interdependency requires a large number of adaptations, such as more exploration work, new and strong competences within digital, more frequent coordination and a more gradual binding towards the Bill of Materials lock in case of early digital production. See Proposition 11 above for key adaptations that were necessary in projects A-C.
- Necessary adaptations to fit the increased levels of all four process characteristics can effectively be done by implementing a number of new agile or agile inspired practices, such as scrum and Big Room Planning.
- Also, the practices of the majority of functional departments supporting a digital-physical product development project need to be adapted to the mixed materiality and the challenging process characteristics. See Proposition 12 above. In particular, helping supporting functions to become more agile in, at least parts of, their operations, can allow them to support both predictable and unpredictable demand.

Table 4 is adapted from Hendler (2019), Appendix B, Table 2 and lists the new practices that was adopted or suggested to be adopted across the experiences of projects A, B and C in COMP. Building on top of the learning from these projects, Project D and E implemented agile practices to further adapt to the new project characteristics, as showed in Figure 11.

Table 4 Overview of new practices and contextual changes across Project A, B and C. Ordered according to the process characteristic to which they are adapting the most (Source: Hendler, 2019).

Practices and context
Uncertainty *Implemented:* • Much ad hoc problem-solving • Increased stakeholder management and network driven execution • Highly experienced project members comfortable working with high uncertainty • Ad-hoc design of new support processes • More schedule buffers • More cross-functional co-location • Front-load work to avoid schedule delays • More front-end project members continuing to execution phase to avoid knowledge loss • Establishment of some post launch operations • More time spent on understanding new market category *Suggested:* • Stronger collaboration/co-creation across digital and physical • Stronger risk focus • Shorten physical prototype development cycles • More and dedicated technical subject-matter experts in front-end to make 'proof of technology' • More T-shaped resources • More and earlier allocated IPR competences • Understand cost-of-delay for milestones • Faster project governance decision making • More risky business cases allowed • Fast reaction to post launch market feedback beyond digital, e.g. marketing or pricing • New return policies • More reactive planning of processes, budgets and people • Shorten long lead-time processes to enable later binding • Digital platform development • More focus on marketing innovation • Mature and anchor post lunch operations
Diversity *Implemented:* • New digital competences • New digital technology to help develop digital prototypes *Suggested:*

- Digital partner contract negotiation skills
- New digital operating model competences and models
- More digitally competent management

Interdependence

Implemented:

- Early and stronger focus on dependencies
- Cadenced coordination meetings
- More coordination competences
- Cross-functional problem solving
- Multi-domain liaison role
- Some digital-physical co-location
- New project organisation
- Clarified roles

Suggested:

- Physical design should not be in the lead per default
- Improve partner collaboration skills

Complexity

Implemented:

- More problem-solving loops
- The best subject matter experts
- New testing methods

Suggested:

- Policies for when to use internal or external competences
- More T-shaped resources
- Better on-line collaboration tools for non-co-located collaboration
- Define digital quality acceptance criteria

4.3.3. EFFECTIVE COORDINATION PRACTICES

- Continuing product development process standardisation helps to maintain stability while providing easy-to-communicate information to help make performance trade-offs between digital and physical development practices when coordinating. Therefore, the standard product development model must be updated to include digital roles, deliverables and integration points or milestones. Furthermore, it must be ensured that the selected gates represent the highest cost of delay milestones that are relevant to the full project. Also, a live phase after product launch must be added.
- Then, agile coordination practices including emergent project planning from scrum and dependency mapping, such as PI Planning from SAFe, or Big Room Planning, enable empowered participants to learn from each other and make cadenced and informed trade-off decisions between preferred digital and physical development practices (see Hendler (2020) for more details).

- Finally, it is recommended that these agile coordination practices are standardised in a cyclical digital-physical meta-process and added to the project management toolbox together with the standardised meta-process model.

As an inspiration, Figure 23 depicts the coordinating meta-process exemplified by Project E in Hendler (2020), Appendix C, Figure 5. Additionally, Table 5 is adapted from Hendler (2020), Appendix C, Table 3, and lists the practices that were implemented in Project D, E, or both, to complement the meta-process and successfully coordinate a digital-physical product development project.

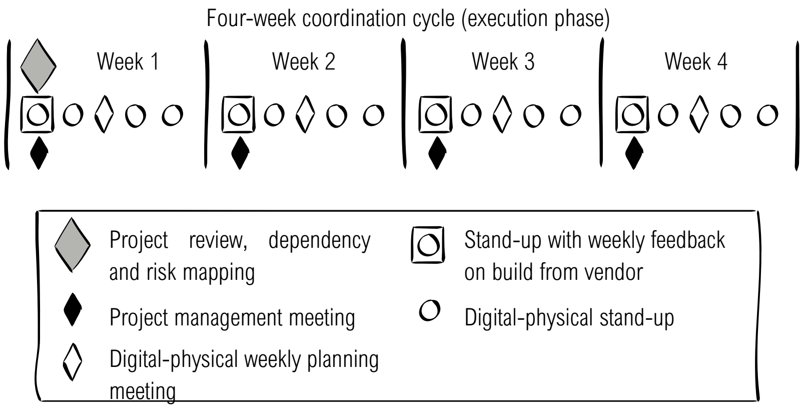

Figure 23 Project E's standardised meta-process of coordinating events (Source: Hendler, 2020)

Table 5 Coordination via strategy, organisation and technology in Projects D and E[6] (Source: Hendler, 2020)

Strategy

- Trust development subprocesses to do their own planning in the best interest of the full project
- Cadenced goal setting (D)
- Cadenced planning and negotiation with focus on dependencies and integration points
- Prioritise cross-functional learning
- Empowerment and transparency
- Focus on coordination practices and continuously adjust
- Exploit best practice agile coordination practices
- Clear digital-physical product integration design principles
- Use Scrum where most uncertainty (D)
- Fast, empowered product decision making and feedback by limiting amount of digital-physical decision-makers (E)
- Support cross-project learning and problem solving
- Effective ad hoc coordination over formalised and cadenced coordination where feasible for COMP-internal (inter)dependencies (E)

Organisational arrangements

- Physical product and digital user experience design integrated in one development subprocess (task force) (E)
- Digital-physical liaison/translator role
- Digital-physical design pairs (D)
- One digital-physical design responsible (E)
- Digital design responsible in project management team (D)
- Broader and overlapping project roles
- Co-location and co-creation when feasible

Technology

Humanware

- Learning-motivated
- Digital-physical experience

Hardware

- Area for project co-location
- Wall space and white boards

Software

- Agile and traditional plans
- IT sharing platforms for cross-digital-physical work
- Online meetings
- Visual and video messaging
- Scrum board
- Exploration Kanban board (D)
- Sticky note risk maps, dependency and project plans
- Team overviews

[6] (D) denotes: only in Project D; (E): only in Project E; all other items: both projects.

4.3.4. THE CAPABILITY TO FIND AND IMPLEMENT SUITABLE PRACTICES AND A DITTO CONTEXT

As to the capability to find and implement suitable practices and a ditto context, it is recommended to:

- Ensure that the first digital-physical project is well suited for ongoing problem solving and learning via highly experienced people and a well-resourced project to be able to succeed although the development practices and context do not fit the new requirements yet. Allow slack with respect to performance targets and set realistic targets.
- Utilise the experience from the people involved in the first digital-physical project and enable and empower them, in a coordinated, cross-functional and pragmatic problem-solving effort, to focus on the most urgent capability gaps while informing, supporting and learning from ongoing projects.
- Build new capabilities integrated into existing structures and processes to maintain and be able to benefit from the existing capabilities.
- Focus on the most urgent parts of the needed capabilities first, i.e. priority one capabilities. Then, in a second initiative or wave implement priority two capabilities. Continue consecutive initiatives while informing, supporting and learning from ongoing projects until the desired performance level is achieved.
- Gradually increase the percentage of digital-physical projects in the project portfolio to adapt to the maturing digital and digital-physical capabilities and scarce capacities.
- Re-organise only if that is relevant to remove impediments. Additional and, possibly more radical, re-organisations may come later.

See Figure 21, Chapter 3, for a depiction of COMP’s effective capability building model and Appendix E for a description of a two day cross-functional workshop in which recommendations for new practices were successfully developed by a cross-functional group.

CHAPTER 5. DISCUSSION OF THE EMPIRICAL ANALYSIS AND DIRECTIONS FOR FURTHER RESEARCH

This chapter addresses the quality of the empirical analysis performed as part of this thesis, in particular the challenge of achieving *"'qualitative rigor' while still retaining the creative, revelatory potential for generating new concepts and ideas"* (Gioia et al., 2012, p.15). As a large part of the research was based on the case study and action research approach as the overall logic, the *rigour* of this research is evaluated in relation to construct validity, external validity and reliability (Yin, 2009). Construct validity refers to the extent to which correct operational measures are established. External validity refers to the extent to which a study's findings can be generalised beyond the immediate case domain. Reliability is the extent to which a study's operations can be repeated with the same results (Yin, 2009). Also, potential biases are addressed.

As a part of this discussion, additional methodological details are presented on the data analysis and derivation of results that was performed as part of the research reported in Hendler (2019) and (2020). These descriptions complement the method descriptions in the two papers (see Appendices B and C). This is done to help an overall evaluation of all the empirical analyses performed in this thesis across Hendler (2019) and (2020), Section 2.5 ("More adaptable physical product development") and Chapter 3 ("Capability to provide the right practices and context"). Finally, the limitations of the research are discussed and directions for further research are presented.

5.1.1. DATA COLLECTION

With the aim to increase methodological reliability and rigour, a case study protocol was initially developed to study Projects A, B and C. This was done based on the template provided by Yin (2009, pp. 80-81) to help guide the researcher through the initial data collection. The protocol ensured diversity and complementarity in the roles of the selected interviewees, ensured a clear logic between the research objective, the interview questions and other collected evidence, ensured consistent interpretations of the various concepts and constructs by providing tentative analytical definitions, ensured many sources of evidence across documents, interviews, direct observation, participant observation, and observations of physical artifacts, and ensured interview guidelines and initial thought on data capture templates. The later protocols followed the same ideas, and treated the action research as an evidence collection vehicle.

To increase the likelihood that all relevant constructs were considered, the case study protocols were informed by the literature review reported in Hendler and Boer (2019). Although the body of literature was immature and scattered, it has successfully inspired the constructs in the research model, which has withstood subsequent case study research. Constructs, such as ‘digital and physical development practices’, ‘adaptability and stability optimised practices’ and ‘agile(-inspired) practices’ are predominantly inspired by literature and have been defined in the case study protocols and reported in the papers and in the body of this thesis.

The interview guides have predominantly included four to eight broad, open-ended questions to allow exploration with follow-up questions and the establishment of potential cause and effect relationships between new practices and their performance effects. As a result, the booked interview time tended to run out faster than desired. However, all the questions were answered within due time, albeit with various levels of detail.

Various project documents were used to secure contextual knowledge and triangulation opportunities. Specifically, the researcher, being embedded in the company context, was able to collect much direct and indirect evidence from informal conversations, with key points from these conversations being noted in the action diary, typically immediately after the conversations took place.

5.1.2. DATA CAPTURE AND REDUCTION

63 of a total of 70 formal interviews have been recorded and transcribed by the researcher. The interview meta data such as duration, date, willingness to participate again, job title of the interviewee at the time of interview, project name and topic were recorded in a spreadsheet. Observation and reflections were noted in the action diary format, which proved suitable across all action research initiatives, i.e. 278 pages. See the daily diary structure in Appendix D. The interview transcriptions, the diary notes and key summary documents, such as retrospective summaries, provided the foundational evidence for what Yin (2009) calls the research “database”, a base of evidence that can be subject to subsequent analyses. In this research, these databases have first and foremost been populated by informant quotes from the interview transcriptions. Diary notes, meeting summaries or very close approximations to informant quotes have also been used in the database. Information from other documents has rarely been put directly into the databases. Diary reflections have in some cases been written into the database e.g. in the research done for Chapter 3, in which the most data was collected via the diary. However, when observation statements or reflections were entered into the database, these were labelled as such to keep an awareness about the different levels of subjectivity.

Below, the data reduction supporting the research done in Hendler (2019) and (2020) is reported.

5.1.2.1 Data reduction – Hendler (2019)

To prepare the complex data for analysis and categorisation, the relevant data was initially divided into single pieces of data by copying statements from interviews and observation notes into separate rows in a spreadsheet. Without changing the wording of the statements, the data in each row was organised into the following four generic categories according to what the data was describing, i.e. columns in the spread sheet:

- Change/challenge/opportunity
- Example (details about the specific example from a project)
- Performance impact (the effect of a change/challenge/opportunity)
- Tested/suggested solution (the practice the project tested to respond to a challenge or opportunity)

This was done in order to be able to piece the data up in a way that made it easier to group and compare, while still retaining key contextual information. Not all columns were filled in per row due to missing data. Each row was furthermore described by the following properties to maintain a chain of evidence for the further data analysis:

- Unique statement identification number
- Source of statement (name of person and e.g. label of workshop, meeting or interview (e.g. interview 1 or interview 2))
- Project name

This process resulted in 469 rows or data statements. Specifically, 173 describing Project A, 162 describing Project B and 123 describing Project C.

5.1.2.2 Data reduction – Hendler (2020)

For Hendler (2020) the analysis also first involved extracting data from the key data documents, including interview transcriptions, workshop summaries, team retrospective summaries, the questionnaire data and the action diary. Similar to the initial analysis done in Hendler (2019), relevant data was copied into rows in a spread sheet. If necessary, summary statements were formulated and labelled as such in order to clarify imprecise or unclear statements. Each row consisted of the following columns focused on coordination:

- Experienced coordination challenges
- Coordination practices tested
- Performance effects of new coordination practices
- Old coordination practice(s)

Furthermore, the rows included information about the data source and a unique identification number. Most of the rows included a relatively large amount of data with up to approximately 500 words across the columns. The extracted data was initially placed into three separate spreadsheets, one for ‘Process w/o hw and Process w/ hw’, one for Project D and one for Project E.

Following the descriptions above, a chain of evidence (cf. Yin, 2009) was established on database level per data fragment across Hendler (2019) and (2020), as also described in the method section in Section 2.5. Similarly, a chain of evidence was kept in the data analysis for Chapter 3, although the extracted data was not forming a typical database, but an overview of all key data ordered in a chronological sequence according to the capability building process. Hence, in all cases, data was reduced by extracting key data from the sources of evidence, and care was taken to document the context of each data fragment to increase construct validity and reliability.

Using this method involves the assumption that: “*people in organizations know what they are trying to do and can explain their thoughts, intentions and actions*” (Gioia, et al., 2012). This assumption was supported by the researcher, who during many informal conversations and interviews has helped the informants to become more aware of their own intentions and actions by posing questions aimed at exploring their own statements (Yalom, 2006). Having retrieved evidence from some of the same informants in two different projects over a period of several years has made such maturation of reflection evident. In all cases, direct quotes from informants have been particularly valued during the database building and subsequent analysis.

This initial data reduction (Voss et al., 2002) was similar to the 1^{st} order analysis as defined by Gioia et al. (2012, p. 20), which tries “*to adhere faithfully to informant terms*”, while making “*little attempt to distil categories*”. The reduction process also enable the researcher to thoroughly familiarise herself with the data. The case study protocols provided draft templates for how to process the collected data corresponding to the spreadsheet column names in Hendler (2019) and (2020), and Section 2.5. However, the final column names were a result of an iterative process.

5.1.3. DATA ANALYSIS

Based on the reduced data in which the integrity of the 1^{st} order information was intact, the data was further grouped in the cases of Hendler (2019) and (2020), and Chapter 2.5, and analysed as a narrative with cause and effect mechanics in the case of Chapter 3. Below, a description of the analyses performed as a part of Hendler (2019) and (2020) are provided.

5.1.3.1 Data analysis – Hendler (2019)

Grouping of the 469 data statements

The rows of data statements were printed out and grouped, project by project, into categories describing similar changes, challenges or opportunities, i.e. the statements for each project were grouped according to the data in the first column of the printed rows. Each group was described by an emerging list of key words scribbled on print-outs of the individual data statements or by highlighting short phrases from key statements with a highlighter pen and placing these on top of a group as a reminder of a topic. Multiple iterations were made to the grouping due to sometimes unclear descriptions or descriptions referring to complex challenges stemming from multiple problems. To remedy that the same data statements sometimes described multiple problems, these specific statements were printed out twice (or more) in order to contribute as evidence for two (or more) groups.

During this grouping it was often challenging to adhere faithfully to informant terms when scribbling key words on the paper slips to aid the categorisation. Many informant statements were long and complex, with much function-specific language, detail and examples. Hence, during this categorisation, words from the literature were introduced to provide more accurate key words on a higher level of abstraction.

This first analysis resulted in 26 categories for Project A, 25 for Project B and 34 for Project C. 85 categories in total.

2nd order analysis with research model themes

With the intention of understanding the data in terms of the research model proposed in Hendler and Boer (2019), the categories were then grouped into three high level themes per project in accordance with the research model:

- Combination practices
- New product development practices
- Contextual practices needed

This step in the process did not result in a revision of the research model, nor in additional high level themes.

Next, each of the 85 categories was analysed, project by project. The categories belonging to the ‘Combination practices’ theme were analysed, one by one, by first copying key representative examples and representative descriptions from a category of statements into the following columns in a spreadsheet. This resulted in a further data reduction.

- Conflicting process practices (description of the differences between digital and physical coordination practices)
- Examples (details about the specific example from a project)
- Combination practices to create fit (description of the practices the project implemented to try to solve the conflicting practices)
- Local performance effects (description of the immediate effects of the implemented coordination practices as experienced by the project members)
- Overall performance effects (comments about the believed impact on the performance of the project's projected business case)
- Further solution suggestions (suggestions on coordination practices that the project members believe would have better performance effects than what they just implemented in their current project)

Analysing the 85 categories in this way required triangulation with other documents such as a project team member overview or a product concept description to mitigate the risk of faulty interpretations. A unique number was assigned to each category to ease further analysis and establish a chain of evidence. Also, the unique numbers from the 469 statements that provided the evidence for the categories were listed as properties of the categories.

The categories belonging to the next two themes, i.e. 'product development practices' and 'contextual practices', were analysed in the same way, but according to the following columns in the spreadsheets:

- New characteristics (description of the new practice characteristics that causes the project to work in new ways)
- Conflict with existing practice(s) (as a result of the new characteristics, what precisely had to be changed and what makes this change difficult when looking at our old practices and/or context?)
- Tested practice to create fit (a detailed description of the new implemented practice)
- Performance impact(s) (what were the immediate and/or overall performance effects)
- Example (description of specific project examples)

The above columns used to analyse the categories within all three high level themes emerged as the analysis progressed, but took their starting point in the case study protocol.

See Appendix F for an overview of how the 85 categories were distributed across projects and themes. Table 6 provides an overview of the three main analytical steps in Hendler (2019) and their resulting number of data statements and categories. The final column corresponds with the categories presented in Appendix F.

Table 6 The three main analytical steps in Hendler (2019) and their resulting number of data statements and categories

Project name	1st order analysis	Categorisation	2nd order analysis
Project A	133 data statements	26 categories	7 categories of combination practices 4 categories of development practices 15 categories of contextual practices
Project B	162 data statements	25 categories	7 categories of combination practices 4 categories of development practices 15 categories of contextual practices
Project C	173 data statements	34 categories	7 categories of combination practices 4 categories of development practices 15 categories of contextual practices

Developing cross-project categories

Then the categories within each theme (combination, development and contextual practices) were compared and grouped across Projects A, B and C. This comparison showed that the categories from the three projects were either similar or analytically complementary. They were analytically complementary when they fitted certain patterns of other projects and, hence, complemented the overall narrative, despite being different. For example, one project was relying heavily on legal expertise, which brought attention to the lack of digital legal knowledge in COMP, whereas other projects did not describe this challenge as they did not rely on such expertise, or had not encountered or realised the problem or risk. However, even though not all the projects had this challenge, it fitted the pattern of 'lack of digital capabilities' in other projects.

This cross-project grouping was performed by paying attention to underlying patterns and relationships between the research model constructs (see Figure 4, Chapter 2). The grouping resulted in 22 aggregate 2nd order categories across Projects A, B and C and across combination, development and contextual practices. See Appendix G for the 22 cross-project categories and their references to the evidence categories summarised in Appendix F. The 22 new categories referred to many of the same subcategories, due to the complexity of these and their examples, which often provided evidence for multiple aggregate themes.

5.1.3.2 Data analysis– Hendler (2020)

In the data analysis for Hendler (2020) on the topic of coordination, the extracted rows of data within the spreadsheet for Projects D, E and 'Process w/o hw and Process w/ hw' were re-read, similar statements were grouped and headlines were given to the larger and more complex data categories, either using terms from the literature where necessary to increase precision or by highlighting some of the words in the data with a bold font. This resulted in 110 categories across the three spreadsheets: 49 in Project D, 51 in Project E., and 10 in Process w/o hw and Process w/ hw. Below, example headlines are provided for each of the three spreadsheets:

Process w/o hw and Process w/ hw

- Project leader needs reference schedule with new but typical process steps and dependencies
- Collaboration with external technology partners preferred due to slow internal process standards
- Missing role to bridge digital technology with physical technology, full stack

Project D

- Coordination challenged due to new technology dependencies and unclear roles
- Lack of cross-domain knowledge
- Collaboration vs. transaction mindset

Project E

- Many and strong digital-physical interdependencies
- Co-location and its compensation
- Project reviews for full team

Next, each spreadsheet was analysed according to the following questions:

1. Why were new coordination practices needed?
2. Which were the new coordination practices tested?
3. Which were the performance effects of the new practices?

To help answer question 1, the process characteristics of interdependency, complexity, uncertainty and diversity by Boer and During (2001) were introduced as a lens (see Section 1.4.5). To be able to discern the coordination practices tested in Projects D and E according to question 2, Mintzberg's (1979) continuum of coordination mechanisms was considered together with coordination practices proposed by Galbraith (1973), Daft (2004), Paashuis and Boer (1997), and agile practices suggested by Sutherland (2015), Larman and Vodde (2016) and Knaster and Leffingwell (2017) as described in Hendler (2020). No direct theory was used to help analyse the answer to question 3 regarding performance effects, in order to keep an open mind to all possible performance effects, both immediate, longer-term effects, direct effects and indirect effects. This analysis resulted in narratives and tables in Hendler (2020), such as "*Table 3 Coordination via strategy, organization and technology in projects D and E*" (Appendix C), "*Table 4 A summary of the coordination challenges and successful, tested solutions*" (Appendix C), and in the narratives describing the tested new coordination practices in Project D and E (Appendix C, section 4 Results).

In the analyses reported in Hendler (2019) and (2020), Chapter 2.5 and Chapter 3, the integrity of the 1st order data was kept by refraining from reducing the complex data into headlines, but highlighting key words or adding a few summary words, i.e. headlines, to the complex data instead. Thus, category headlines were always accompanied by representative 1st order evidence. In this way the complexity of the data was sought maintained, to allow rich and reliable interpretations. As described in Hendler (2019) and (2020), the categories consisted of representative evidence that was copied-in or maintained from the initial extraction of evidence from the large amounts of collected data. The risk of interpretation errors or misunderstanding of the complex data, especially with only one researcher doing the analysis, was sought mitigated by an iterative analysis process and by the researcher being embedded in the company context, which allowed for a rich understanding of the collected data via multiple data sources and triangulation options.

To help ensure construct validity the chain of evidence was maintained from the collected data to the categories and results, as exemplified by Appendices F and G. To further increase construct validity, COMP has performed reviews after each digital-physical project, validating links between, for example, the lack of sufficient cross-functional integration and product quality problems. Finally, selected interviewees have read the analyses to validate constructs, data, relationships and conclusions.

5.1.4. DERIVATION OF RESULTS

The empirical data analysis was performed to inductively mature and illustrate the research model proposed in Hendler and Boer (2019). Thus, this model assisted in the formulation of dynamic relationships among categories of evidence in the data structure to arrive at recommendations and propositions. These final steps were performed while consulting the literature to refine the articulation of the emerging concepts and relationships (Gioia et al, 2012). Below, a description of how the results were inferred in Hendler (2019) and (2020) is provided.

5.1.4.1 Hendler (2019)

The final 22 categories underwent various analyses to be able to finally infer 12 propositions. During this analysis the following questions were considered:

- What is the new phenomenon being described?
- Which part of the research model does it describe?
- What is the dissimilarity between the two processes (digital and physical) that is described and why does this exist?
- What is the combination mechanism used?
- What is the change needed?
- What are the performance effects of combining the two processes?
- What is the strength of the evidence?

The analysis was performed in a spreadsheet with each category represented by rows and the answers to the questions above, where applicable, represented by columns in a matrix. Again, each row was assigned a unique number as well as numbers referring to the evidence. Finally, each row was concluded with three iterations of proposition formulation relating to the research model and the read literature where opportune. During this final process of abstracting the data into formulations of concepts and principles that are potentially transferable into other domains (Gioia et al., 2012), a number of categories revealed similar patterns and were combined. One was discarded due to weak evidence.

5.1.4.2 Hendler (2020)

The propositions in Hendler (2020) were based on the spreadsheet data and the case narratives. Several conclusions were made over several iterations by comparing the empirical evidence with the literature. Also, interview statements were revisited in the transcribed texts to ensure sufficient contextual understanding. During this final analysis, quick feedback was retrieved by continuing informal conversations with members of the projects, which reduced the risk of misinterpretations. Finally, seven suggested propositions were reduced to a final four as a result of a maturation of the narratives and their conclusions.

In all cases, the results in Hendler (2019) and (2020), Chapter 2.5 and Chapter 3 were either directly validated 1) by informants reading them, 2) by discussing them with informants to get their feedback or 3) via final interviews to validate the results. This was done to increase reliability and validity.

5.1.5. EXTERNAL VALIDITY – DEFINING THE DOMAIN

This thesis has studied five digital-physical product development projects (projects A-E) and one capability building project. All are embedded within one company over a time period of six years. This resembles what Yin (2009, p. 46) labels a "*single-case (embedded) design*", where multiple units of analysis are studied, which can enhance insight into the single case. The main argument for an in-depth single case design is that it is a "*revelatory case. This situation exists when an investigator has an opportunity to observe and analyze a phenomenon previously inaccessible to social science inquiry*…" (Yin, 2009, p. 48). Yin (2009, p. 61) adds "*Single-case designs are vulnerable if only because you will have put 'all your eggs in one basket'… criticisms about single-case studies usually reflect fears about the uniqueness or artefactual conditions surrounding the case".* Accordingly, the extent to which a study's findings can be generalised beyond the immediate case for further testing is dependent upon the definition of the domain.

The aim of the single-case study is to strive for analytical generalisation of "*a particular set of results to some broader theory*" (Yin, 2009, p.43). This especially applies in Section 2.5 and Chapter 3 in which the presented research objectives are addressed with only one unit of analysis. The *broader theory* in this study is an emerging and scattered field of literature in which the phenomenon of study, i.e. digital-physical product development, is currently being described and no clear body of theory exists (Hendler and Boer, 2019). Hence, the existing domain of theory to which the results from this study is to be generalised, and from which relevant cases can be identified, is not yet clear. This thesis attempts to contribute by proposing a research model, a description of the phenomenon in question and contributes with propositions and elaborate case descriptions to help give an understanding of the complex domain, in which the results may be replicated. Gioia et al. (2012, p.24) add "*Is it possible to generalize from a case study? Of course it is – if the case generates concepts or principles with obvious relevance to some other domain. It is also important to emphasize that our corollary intent is to generalize to theory*."

The empirical results in this thesis present aspects of product development that, based on subjective evaluations by informants and supported by strong and realised business cases, are considered to be successful within a COMP context. Creating objective proof for the success of the various digital-physical product development practices and capabilities within a hyper-unpredictable and multi-facetted unfolding social phenomenon lies beyond the scope of this study. The case specific factors that have influenced the research results are many and include company maturity and degree of process standardisation, lead-time of the manufacturing processes, product technology, product volume, market size and company performance and brand. Many specifics about the operations of COMP have been communicated in the analyses to optimise the relatability of the research. Still, the complexity of such a domain coupled with COMP's confidentiality policy hinders the disclosure of the specific product type and industry, and compromises the precision by which the domain has been described. To mitigate this, Chapter 1 describes example products representing similar levels of digital-physical product integration, to enable the reader to relate to the level and type of digital-physical subprocess interdependency.

There are obvious limitations to studying a single company in terms of the ability to generalise the research results to a broader theory applicable to other systems, and in the case of Section 2.5 and Chapter 3, only one unit of analysis was studied. However, "*For a given level of resources, single cases allow for more depth*" (Caniato et al., 2017, p.1839), whereas a multiple-case study enables a clearer domain definition. However, the emerging field of digital-physical product development requires in-depth exploratory research that offers a "*creative, revelatory potential for generating new concepts and ideas*" (Gioia et al., 2012, p. 15). Single-case studies are appropriate for exploratory studies, and the appropriateness of the trade-off with external validity is dependent on "*whether the insights generated (with the benefit of depth and/or longitudinality) are sufficiently novel and impactful […] to compensate for the limitations of the design*" (Caniato et al., 2017, p.1839).

Thus, presenting a significant amount of data through the lens of a new research model accompanied by a significant amount of tentative propositions and recommendations may be considered to justify the trade-off with external validity when contributing to an emerging and scattered field of research. In Section 5.2 various directions for further research are suggested to further explore and test the tentative theory proposed in this thesis beyond the context of COMP.

Finally, this research is not intended to test the research model. The research model has been used to guide the empirical analyses. It has helped organise the analyses through the relationships and constructs embedded in the model, according to the operationalization that the state-of-the theory allowed to develop. With this in mind, the researcher was open to finding constructs, operationalisations and relationships that were not part of the original model. The model is also illustrated by the research, as it gives concrete examples of constructs and their relationships to help "*the reader to imagine more easily how the conceptual argument might actually apply in empirical settings*" and to "*make it easier for the reader to assess the plausibility of the theory's relationships*" (Caniato et al., 2017, p. 1838).

5.1.6. ACTION RESEARCH AND POTENTIAL BIASES

The action cycles performed as part of this research were not additional structures imposed onto processes within COMP. The processes in COMP included sufficiently similar learning cycles to enable reflection and correct or change course at least every two weeks. In addition to these more formal structures, the action researcher led a number of mini-cycles in collaboration with one or two other participants to address specific topics or ensure room for reflection. These mini-cycles were not perceived as specific to the research effort, but as a part of addressing current and relevant problems at COMP. Coughlan and Coghlan (2002) describe the importance of creating an action research (AR) contract. "*This contract involves the key members of the organisation recognising the value of the AR approach and being willing to have the action researcher working with them in a process consultation mode*" (p. 228). The action research performed as part of this thesis, however, can be described nearly in opposite terms. Only some of the organisational members were actively aware of the action researcher playing two roles. The action researcher was perceived as internal to COMP, not external. The researcher both performed a process consultant role as well as a doctor-patient consultant role (Schein, 1999), and no agreement needed to be made regarding working in learning cycles, as this way of working was embedded into Project D, E and the capability building effort as inspired by agile ways of working. Finally, the action researcher was invited to participate as a team member or driver in the role of an agile consultant and change agent, irrespective of the research agenda of the researcher.

Additionally, according to Coghlan and Brannick, (2010), the consultant role has similarities with a research role and, as a result, the risk of conflicts due to role-duality are lower, i.e. biases. COMP gave the present author the task to help solve a number of complex problems related to digital-physical product development. With a strong collaboration between the researcher and the project members, everyone worked towards developing and implementing effective practices iteratively, i.e. continuously improving the practices until they worked, or do something else. This enabled the implementation of effective practices in multiple projects. With all stakeholders interested in hearing about good results, this inevitably may have caused a bias towards reporting overly positive results. However, the research reporting was conducted by the researcher in parallel to the internal COMP reporting and without attention from COMP employees other than what the researcher asked for in terms of key informants reviewing analyses and results as previously described. Finally, taking the perspective of COMP and ensuring non-disclosure of confidential information a COMP employee formally read and approved the analyses. This employee was previously a manager of a digital-physical project and, furthermore, had some knowledge of the experimentation in Projects D and E concerning their coordination practices. Therefore, she was able to make further remarks to ensure quality.

COMP has partly sponsored this PhD project. However, soon after the PhD was initiated, the specific sponsor, left the company. No other sponsor role, advisor or sparring partner was identified from COMP, neither formally nor informally. Therefore, with the exception of securing that the identity of COMP remained undisclosed, as well as ensuring that confidential information was omitted should the identity be revealed, COMP has had no direct influence on the data collection, the analyses conducted, and the discussion of the results in this thesis.

In this PhD project, the action researcher possessed prior knowledge of the operations, people and culture within COMP, particularly its product development organisation. Coghlan and Brannick (2010) note that being too close to research data may be a disadvantage. Therefore, in accordance with Coghlan and Brannick (2010), "*biases and preunderstandings were sought mitigated via a reflection space in the research diary considering 'group think' dynamics and 'what-I-think-I-know' risks*" (Hendler (2020), Appendix C, p. 238). Similarly, interviews were executed while assuming the more objective researcher role.

5.1.7. CONCLUSION

Using the case study and action research methods this empirical research demonstrates a significant in-dept understanding into the development of digital-physical product capabilities and practices in a single case company. Reliability, construct and external validity have been considered by using multiple sources of evidence, large amounts of data, establishing chains of evidence, key informants reviewing the analyses and results, using literature and case study protocols, and establishing databases in which informant terms were preserved. Using these methods, the researcher has sought to compensate for not bringing in research colleagues to provide fresh perspectives on the data analysis. Also, particularly due to an 'arm's length' sponsorship, the research has remained sufficiently unbiased from case company interests. However, due to using the case study method within a single company and, in some cases, only relying on one unit of analysis, i.e. one project, further research is needed to explore the results and strengthen the external validity.

5.2. LIMITATIONS AND DIRECTIONS FOR FURTHER RESEARCH

5.2.1. LIMITATIONS

Studying one company over the course of six years, enables development of in-dept insight, but also presents limitations in terms of context. COMP represents highly stability-optimised practices including a large and highly optimised manufacturing facility enabled by very stable product platforms and markets. Consequently, the differences are significant and many, between the state-of-the-art software development practices of world class vendors and COMP's own development practices. These differences may be significantly smaller in less mature manufacturing companies, in companies with short manufacturing lead times or born-digital-physical companies. Thus, other manufacturers may not face the same level of performance trade-offs when combining digital and physical product development.

Furthermore, COMP is in an industry in which is it unlikely that digital technology is going to completely disrupt its core business, i.e. COMP needs to maintain its established competences in its purely physical value chain and digitalise only a smaller part of its full product portfolio. Other companies might find themselves completely disrupted by digitalisation, which may significantly impact the results from this research. The feasibility of such companies to make different performance trade-offs such as significantly delaying the Bill of Materials or making physical product development more agile may be very different than it is for COMP.

Another important contextual factor is that COMP is in the beginning of augmenting its products with digital technologies. As a consequence, its digital-physical product strategies, business models, operating principles, product architectures and platforms are immature. This limits the extent to which COMP has been able to separate the digital and physical development subprocesses, i.e. the level of process interdependencies has been significant and new practices have had to be adapted to this level.

Finally, this research has studied product development in which physical development mostly has been in the lead. Other options involve that digital is in the lead.

5.2.2. MEASURING PERFORMANCE EFFECTS

Another specific limitation in this thesis concerns how the performance impact of the new digital-physical product development capabilities and practices was measured in the empirical research. Performance has been measured via qualitative data in terms of observations, interviews and survey feedback. No quantitative performance data was available for benchmarking on the level of detail needed to measure the impact of the individual or the collective new capabilities and practices. The available performance data such as net promotor scores, employee satisfaction scores, and severity and number of quality issues was either measured too infrequently or at too high a level to measure direct performance effects of the implemented capabilities and practices. This made a quantitative comparison with other digital-physical product development projects impossible. Due to the lack of hard numbers and with ‘performance’ being a key construct in many of the proposed propositions the propositions must be used thoughtfully and with the intention of further testing. Similarly, when relating to the proposed recommendations for practitioners, these must be considered as inspirational and implemented with the intention of experimentation to ensure the necessary adaptation.

5.2.3. DIRECTIONS FOR FURTHER RESEARCH

This research answers recent calls for theory development from Nambisan et al. (2017) and Holmström (2018) for this new field. However, the research model is not yet mature and needs further operationalisation and testing. The topic and the tentative and descriptive constructs, relationships, findings and propositions all need further exploration, explanation and validation. The findings and propositions do not exhaust the topic of digital-physical product development but provide a platform that further theory development can build upon.

“[*E*]*xploration in the form of case studies or action research is needed to understand which coordination practices or scenarios are most effective and in which contexts*” (Hendler (2019), Appendix B, p. 216). Specifically, future research should include exploration of all three research areas within various contexts. These contexts may include “*a smaller or less mature manufacturer, a software company that is adding a physical product dimension, or a born digital-physical product development company*” (Hendler (2019), Appendix B, p. 216). As considered in Hendler (2020, Appendix C, p. 259), there might be other development practices, contextual practices, “*coordination practices or combinations thereof, that may prove to be equally or more suitable in different contexts*”. Also, other capability building processes may be more suitable. With the current acceleration of the spread of digitalisation in manufacturing companies, opportunities are growing for researchers to develop theory using action research to help test practices, while solving problems for manufacturers (Hendler and Boer, 2019).

As described in Hendler and Boer (2019), larger scale quantitative study such as a survey, is not the most apparent choice for immediate further research as the field is relatively immature and in a descriptive theory development stage (Christensen, 2006). However, eventually larger scale studies will help to mature the field from tentative theory and enable testing of propositions (Hendler (2019).

Below, specific questions for further exploration are proposed for each of the research areas.

5.2.3.1 Suitable development practices and a context that fit the process characteristics

This thesis points towards a number of practices that need to adapt to fit the combined digital-physical product development process. The literature review suggested that, for instance, combinatorial and horizontal innovation (Yoo et al., 2012) may be better suited, and COMP experienced a significant amount of changes in the development process and its context such as test methods and data analytics. The specific structures, strategies and practices of a digital-physical manufacturer, including the development process itself, is not yet clear. Key questions for further research include:

- Which are the specific characteristics from a software company that a digitalising manufacturer need to include?
- How does an effective product development process model look like for digital-physical product development in various contexts, including potential phases, tools and technology, roles, coordination mechanisms and practices, and key integration points or milestones across subprocesses? This includes which contingencies affect the effectiveness of a digital-physical product development system, and how?
- Which new practices, including horizontal and combinatorial innovation (Yoo et al., 2012) but also potentially others hitherto unidentified, may be more fitting to digital-physical product development in various contexts?

Another avenue involves the lens through which this research has investigated digital-physical product development. This research offers a process perspective on the phenomenon. Also, this research has applied organisation and innovation theory as the primary lenses. However, "*[o]ther relevant lenses include a resource or knowledge-based perspective, which would help study the role of IT systems"* and tools (Hendler (2019), Appendix B, p. 217). A decision-making and a learning lens could help to further explore the performance trade-offs in digital-physical product development. The various lenses could lead to questions such as:

- Which decision-making system (process, organisation) effectively supports digital-physical product development performance trade-offs?
- Which tools effectively support digital-physical product development?
- Which practices can best accommodate digital-physical learning?

5.2.3.2 Effective coordination practices

The challenge is to combine the two development processes while optimising the combined digital-physical product development performance. The thesis has provided specific evidence concerning how to effectively combine digital and physical product development processes and how to reduce the differences between the processes by adopting each other's practices to some extent. However, other methods may be equally or more successful and other explanations may be relevant. Important questions are still unanswered or not fully explored:

- Which practices can effectively reduce the differences or the consequences of the differences between digital and physical product development without significantly trading off the product development performance of one or both of the processes?
- When is it the most effective solution that digital adapts to physical development, vice versa, or that neither adapts at all?
- How and to what extent is it feasible to reduce the digital-physical process interdependencies to avoid performance trade-offs by using, for instance, product architectures and platforms (Yoo et al., 2010; Henfridsson et al., 2018)?

Another related topic this research leaves unexplored is inter-firm relationships. When a manufacturer, whose core competencies are related to physical products, digitalises its products, it is likely to involve partnerships with software companies. These new relationships can be characterised by parameters such as contractual agreements, cultural differences, manufacturing vs. creative industry, different language and time zones and, thus, geographic distances. These all impact the digital-physical trade-offs and how they fall. For instance, work-for-hire vs. profit-sharing contracts infer different power balances, which undoubtedly impacts how stability-adaptability performance trade-offs are made. The present research was not able to produce substantial evidence on this topic. Hence, more research is required to help illustrate the research model from a partnership perspective.

- Which inter-firm partnership and collaboration models can best accommodate digital-physical product development?

5.2.3.3 The capability to find and implement suitable practices and a context

In COMP the capability building model applied was a result of a pragmatic approach and strong bottom-up motivation and energy. Another approach, for instance a more top-down approach, might have resulted in other benefits.

- In various contexts, which practices effectively and efficiently help a company find and implement the needed digital-physical product development capabilities?

5.3. EPILOGUE

Seven years ago, I created the thesis statement for this PhD: *Projects developing products with both digital and physical components require different management approaches.* I set out to explore this statement and have found that digital-physical projects are indeed managed, organised, governed and coordinated differently. Their development practices are different and the support they require from functional departments is different and more collaboration is required. Digital-physical projects use new terminology and draw new process models on the whiteboards. COMP is still in the process of maturing its new capability, and capability building plans stretch into the coming years.

I hope this work will help practitioners with a fundamental understanding of some of the underlying challenges in digital-physical product development, which may, however, not always be the most critical or visible challenges in a complex project, but need to be managed actively.

REFERENCES

Abrell, T., Pihlajamaa, M., Kanto, L., Brocke, J. and Uebernickel, F. (2016), ‘The role of users and customers in digital innovation: Insights from B2B manufacturing firms’, Information and Management, Vol. 53 No. 3, pp. 324-335.

Andreasson, L. and Henfridsson, O. (2008), ‘Digital differentiation, software product lines, and the challenge of isomorphism in innovation: A case study’ in ECIS 2009, Proceedings of the European Conference on Information systems, pp. 3027-3039.

Beck, K., Beedle, M., Van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A., Jeffries, R., Kern, J., Marick, B., Martin, R. C., Mellor, S., Schwaber, K., Sutherland, J. and Thomas, D. (2001), ‘Manifesto for agile software development’. http://www.agilemanifesto.org. Retrieved in November 2019.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M. and Wilson, H. (2007), ‘State-of-the-art in product-service systems’, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 221 No. 10, pp. 1543-1552.

Bassey, M. (1981), ‘Pedagogic research: On the relative merits of search for generalisation and study of single events’, Oxford Review of Education, Vol. 7 No. 1, pp. 73-94.

Bernardes, E. S. and Hanna, M. D. (2009), ‘A theoretical review of flexibility, agility and responsiveness in the operations management literature’, International Journal of Operations & Production Management, Vol. 29 No. 1, pp. 30-53.

Bialasiewicz, J.T. (2017), ‘Interaction of concurrent processes in cyber-physical systems’, Proceedings of the 14th IEEE International Conference on Industrial Informatics, Polish-Japanese Academy of Information Technology, Warsaw, Poland, pp. 516-521.

Boer, H. and During, W.E. (2001), ‘Innovation. What innovation? A comparison between product, process and organisational innovation’, International Journal of Technology Management, Vol. 22 No. 1-3, pp. 83-107.

Broy, M. (2005), ‘Automotive software and systems engineering’, Proceedings of the Third ACM & IEEE International Conference on Formal Methods and Models for Co-design, Verona, Italy, pp. 143-149.

Broy, M., Krüger, I.H., Pretschner, A. and Salzmann, C. (2007), 'Engineering automotive software', Proceedings of the IEEE, Vol. 95 No. 2, pp. 356-373.

Christensen, C.M. (2006), 'The ongoing process of building a theory of disruption', Journal of Product Innovation Management, Vol. 23 No. 1, pp. 39-55.

Clark, K. B., and Fujimoto, T. (1991). Product development performance, Harvard Business School Press, Boston, MA.

Coghlan, D. and Brannick, T. (2010), Doing Action Research in Your Own Organization, SAGE, London.

Cohn, M. (2010) Succeeding with Agile, Pearson Education, Boston.

Conforto, E.C., Salum, F., Amaral, D.C., Da Silva, S.L., and De Almeida, L.F. (2014), 'Can agile project management be adopted by industries other than software development?', Project Management Journal, Vol. 45 No. 3, pp. 21-34.

Cooper, R.G. (1990), 'Stage gate systems: A new tool for managing new products', Business Horizons, Vol.33 No. 3, pp. 44-54.

Cooper, R.G. (2014), 'What's next?: After stage-gate', Research Technology Management, Vol. 57 No. 1, pp. 20-31.

Cooper, R.G. (2016), 'Agile-stage-gate hybrids: The next stage for product development', Research Technology Management, Vol. 59 No. 1, pp. 21-29.

Cooper, R.G. and Sommer, A.F. (2018), 'Agile-stage-gate for manufacturers: Changing the way new products are developed. Integrating agile project management methods into a stage-gate system offers both opportunities and challenges', Research Technology Management, Vol. 61 No. 2, pp. 17-26. Journal website: www.tandfonline.com

Cordeiro, L., Barreto, R., Barcelos, R., Oliveira, M., Lucena, V. and Maciel, P. (2007), 'Agile development methodology for embedded systems: A platform-based design approach', in Leaney, J., Rozenblit, J.W. and Peng, J. (Eds.), Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems, Institute of Electrical and Electronics Engineers Inc., Tucson, AZ, USA, March 26-29, pp. 195-202.

Cordeiro, L., Barreto, R. and Oliveira, M. (2008), 'Towards a semiformal development methodology for embedded systems', in Gonzalez-Pérez, C and Jablonski, C. (Eds.), Proceedings of the Third International Conference on Evaluation of Novel Approaches to Software Engineering, Funchal, Portugal, May 4-7, pp. 5-12.

Coughlan, P. and Coghlan, D. (2002), ‘Action research: Action research for operations management’, International Journal of Operations & Production Management, Vol. 22 No. 2, pp. 220-240.

Dagnino, A. (2001), ‘Coordination of hardware manufacturing and software development lifecycles for integrated systems development’, Proceedings of the 2001 IEEE International Conference on Systems, Man, And Cybernetics: E-Systems and E-Man for Cybernetics in Cyberspace, Tucson, USA, October 7-10, pp. 1850-1855.

Dawid, H., Decker, R., Hermann, T., Jahnke, H., Klat, W., König, R. and Stummer, C. (2017), ‘Management science in the era of smart consumer products: Challenges and research perspectives’, Central European Journal of Operations Research, Vol. 25 No. 1, pp. 203-230.

Diegel, O., Singamneni, S. and Withell, A. (2008), ‘A mechatronics approach to rapid product development: A case study’, Proceedings of the 15th International Conference on Mechatronics and Machine Vision in Practice, Massey University, Auckland, New Zealand, December 2-4, pp. 565-570.

Durrett, J.R., Burnell, L.J. and Priest, J.W. (2002), ‘A hybrid analysis and architectural design method for development of smart home components’, IEEE Wireless Communications, Vol. 9 No. 6, pp. 85-91.

Eisenhardt, K.M. (1989), ‘Building theories from case study research’, The Academy of Management Review, Vol. 14 No. 4, pp. 532-550.

Eklund, U. and Berger, C. (2017), ‘Scaling agile development in mechatronic organizations. A comparative case study’, Proceedings of the 39th IEEE/ACM International Conference on Software Engineering: Software Engineering in Practice Track, Buenos Aires, Argentina, May 20-28, pp. 173-182.

Eklund, U. and Bosch, J. (2012), ‘Introducing software ecosystems for mass-produced embedded systems’, in Cusumano, M.A., Iyer, B. and Venkatraman, N. (Eds.), Proceedings of the 3rd International Conference, ICSOB 2012, Springer International Publishing, Cambridge, MA, USA, June 18-20, pp. 248-254.

Eklund, U., Olsson, H.H. and Strom, N.J. (2014), ‘Industrial challenges of scaling agile in mass-produced embedded systems’, in Dingsoyr, T. and Moe, N.B., Tonelli, R., Counsell, S., Gencel, C. and Petersen, K. (Eds.), Proceedings of the 15th International Conference on Agile Software Development, Springer International Publishing, Rome, Italy, May 26-30, pp. 30-42.

Evans, R. (2009), ‘Make functionality, not hardware’, Military & Aerospace Electronics, Vol. 20 No. 9, pp. 16-17.

Gioia, D. A., Corley, K. G. and Hamilton, A. L. (2012), 'Seeking qualitative rigor in inductive research: Notes on the Gioia methodology', Organizational Research Methods, Vol 16 No. 1, pp. 15-31.

Greene, B. (2004), 'Agile methods applied to embedded firmware development', Proceedings of the Agile Development Conference, Salt Lake City, USA, June 22-26, pp. 71-77.

Haghighatkhah, A., Banijamali, A., Pakanen, O., Oivo, M. and Kuvaja, P. (2017), 'Automotive software engineering: A systematic mapping study', Journal of Systems and Software, Vol. 128 No. 6, pp. 25-55.

Have, P.T. (2004), Understanding Qualitative Research and Ethnomethodology, SAGE Publications Ltd., London.

Heeager, L.T., Svejvig, P., and Schlichter, B.R. (2016), 'How agile methods inspire project management – The half double initiative', eProceedings of the 11th International Research Workshop on Information Technology Project Management (IRWITPM), Association for Information Systems, Dublin, pp. 43-55.

Hendler, S. (2019), 'Digital-physical product development: A qualitative analysis', European Journal of Innovation Management, Vol. 22 No. 2, pp. 315-334.

Hendler, S. (2020), 'Exploring coordination practices in digital–physical product development', Journal of Manufacturing Technology Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/JMTM-06-2019-0229

Hendler, S. and Boer, H. (2019), 'Digital-physical product development: a review and research agenda', International Journal of Technology Management, Vol. 80 No. 1-2, p. 12-35.

Henfridsson, O., Nandhakumar, J., Scarbrough, H. and Panourgias, N. (2018), 'Recombination in the open-ended value landscape of digital innovation', Information and Organization, Vol. 28 No. 2, pp. 89–100.

Holmström, J. (2018), 'Recombination in digital innovation: challenges, opportunities, and the importance of a theoretical framework', Information and Organization, Vol. 28 No. 2, pp. 107-110.

Huang, P.M., Knuth, A.A., Krueger, R.O. and Garrison-Darrin, M.A. (2012a), 'Agile hardware and software systems engineering for critical military space applications', The International Society for Optical Engineering 2012, Sensors and Systems for Space Applications V, Baltimore, USA, pp. 1-9.

Huang, P.M., Darrin, A.G. and Knuth, A.A. (2012b), ‘Agile hardware and software system engineering for innovation’, Proceedings of the 2012 IEEE Aerospace Conference, Big Sky, USA, March 3-10, pp. 1-10.

Jepsen, O. (2018), Scaling agile – big room planning. Retrieved December 2019, from https://www.infoq.com/articles/making-scaling-agile-work-4/.

Joglekar, N.R. and Rosenthal, S.R. (2003), ‘Coordination of design supply chains for bundling physical and software products’, Journal of Product Innovation Management, Vol. 20 No. 5, pp. 374-390.

Karlsson, C. and Lovén, E. (2005), ‘Managing new technology integration: Integrating software in manufactured products’, International Journal of Innovation Management, Vol. 9 No. 3, pp. 343-370.

Karlström, D. and Runeson, P. (2006), ‘Integrating agile software development into stage-gate managed product development’, Empirical Software Engineering, Vol. 11 No. 2, pp. 203-225.

Katumba, B. and Knauss, E. (2014), ‘Agile development in automotive software development: Challenges and opportunities’, in Jedlitschka, A., Kuvaja, P., Kuhrmann, M., Mannisto, T., Munch, J. and Raatikainen M. (Eds.), Product-Focused Software Process Improvement. Lecture notes in Computer Science, University of Gothenburg, Gothenburg, Sweden, pp. 33–47.

Kettunen, P. (2003), 'Managing embedded software project team knowledge', Proceedings of PROFES 2006, Nokia Group, Finland, Vol. 150 No. 6, pp. 359-366.

Knaster, R. and Leffingwell, D. (2017), SAFe Destilled: Applying the Scaled Agile Framework® for Lean Software and Systems Engineering, Addison-Wesley Professional, Boston, MA.

Kniberg, H. (2015), Scrum and XP from the trenches: How we do scrum, C4Media, USA.

Könnölä, K., Suomi, S., Mäkilä, T., Jokela, T., Rantala, V. and Lehtonen, T. (2016), ‘Agile methods in embedded system development: Multiple-case study of three industrial cases’, Journal of Systems and Software, Vol. 118 (August), pp. 134-150.

Kubie, E.C. (1994), ‘Recollections of the first software company’, IEEE Annals of the History of Computing, Vol. 16, No. 2, pp. 65-71.

Kuwashima, K. and Fujimoto, T. (2013), 'Performance measurement in product development research: a literature review', Annals of Business Administrative Science, Vol. 12 No. 4, pp. 213–223.

Larman, C. and Vodde, B. (2016), Large-Scale Scrum: More with LeSS, Addison-Wesley Professional, Crawfordsville, IN.

Lee, J. and Berente, N. (2012), 'Digital innovation and the division of innovative labor: Digital controls in the automotive industry', Organization Science, Vol. 23 No. 5, pp. 1428-1447.

Lenfle, S. and Loch, C. (2010), 'Lost Roots: How Project management came to emphasize control over flexibility and novelty', California management review, Vol. 53, No. 1, pp. 32-55.

Lerch, C. and Gotsch, M. (2015), 'Digitalized product-service systems in manufacturing firms. A case study analysis', Research-Technology Management, Vol. 58 No. 5, pp. 45-52.

Lewin, K. (1946/1997). Action research and minority problems. In G. Lewin (Ed.), Resolving social conflicts: Selected Papers on Group Dynamics. Reprinted 1997. Wasington DC: American Psychological Association. pp. 144-154.

Lwakatare, L.E., Karvonen, T., Sauvola, T., Kuvaja, P., Olsson, H.H., Bosch, J. and Oivo, M. (2016), 'Towards DevOps in the embedded systems domain: Why is it so hard?', in Sprague, R.H. and Bui, T.X. (Eds.) ,Proceedings of the 49th Annual Hawaii International Conference on System Sciences, Oulu, Finland, pp. 5437-5446.

McNiff, J. and Whitehead, J. (2011), All You Need to Know about Action Research, Sage Publications Ltd, London.

Mintzberg, H. (1979), The Structuring of Organizations, Prentice-Hall, Englewood Cliffs, N.J.

Maleki, E., Belkadi, F. and Bernard, A. (2017), 'Systems engineering as a foundation for PSS development project: Motivations and perspectives', in McAloone, T.C., Tseng, M.M., Mortensen, N.H., Shimomura, Y. and Pigosso, D.C.A. (Eds.), Proceedings of the 50th CIRP Conference on Manufacturing Systems 2017, Nantes, France, pp. 205-210.

McGaughey, R. E. (1999), 'Internet technology: Contribution to agility in the twenty-first century', International Journal of Agile Management Systems, Vol. 1 No. 1, pp. 7-13.

Mocker, M. and Fonstad, N.O. (2018), ‘Driving digitization at Audi’, Proceedings of ICIS 2017: Transforming Society with Digital Innovation, Association for Information Systems, pp. 1-15.

Morieux, Y. and Tollman, P. (2014), Six Simple Rules: How to Manage Complexity without Getting Complicated, Harvard Business Review Press, Boston, MA

Nambisan, S., Lyytinen, K., Majchrzak, A. and Song, M. (2017), ‘Digital innovation management: Reinventing innovation management research in a digital world’, MIS Quarterly, Vol. 41 No. 1, pp. 223-238.

Patton, J. (2014), User Story Mapping: Discover the Whole Story, Build the Right Product, O’Reilly Media Inc., Sebastopol, CA.

Perrow, C. (1967), ‘A framework for the comparative analysis of organizations’, American Sociological Review, Vol. 32 No. 2, pp. 194-208.

Poppendieck, M. and Poppendieck, T. (2003), Lean Software Development: An Agile Toolkit, Addison Wesley, Crawfordsville, IN.

Porter, M.E. and Heppelmann, J.E. (2014), ‘How smart, connected products are transforming competition’, Harvard Business Review, Vol. 92 No. 11, pp. 65-88.

Porter, M.E. and Heppelmann, J.E. (2015), ‘How smart, connected products are transforming companies’, Harvard Business Review, Vol. 93 No. 10, pp. 96-114.

Rauscher, T.G. and Smith, P.G. (1995), ‘From experience time-driven development of software in manufactured goods’, The Journal of Product Innovation Management, Vol. 12 No. 3, pp.186-199.

Reinertsen, D.G. (2009), The Principles of Product Development Flow: Second Generation Lean Product Development, Celeritas Publishing, Redondo Beach, CA.

Remington, K. (2011), Comprehend Complexity, Gower Publishing, Aldershot, UK.

Rigby, D.K., Sutherland, J. and Takeuchi, H. (2016), ‘Embracing agile: How to master the process that is transforming management’, Harvard Business Review, Vol. 94 No. 5, pp. 40-50.

Rottier, P.A. and Rodrigues, V. (2008), ‘Agile development in a medical device company', in Melnik, M., Kruchten, G. and Poppendieck, P. (Eds.), Proceedings of the Agile 2008 Conference, Toronto, Canada, pp. 218-223.

Rottman, J.W. (2006), 'Successfully outsourcing embedded software development', Computer, Vol. 39 No. 1, pp. 55-61.

Schein, E. H. (1999), Process consultation revisited: Building the helping relationship, Addison-Wesley, Reading, MA.

Schwaber, K. and Beedle, M. (2001), Agile Software Development with Scrum, Pearson Education, Upper Saddle River, NJ.

Schwaber, K. and Sutherland, J. (2017), The scrum guide™: The definitive guide to scrum: the rules of the game. Retrieved, 2019, from https://www.scrumguides.org/docs/scrumguide/v2017/2017-Scrum-Guide-US.pdf#zoom=100.

Simon, H. A. (1996), The Sciences of the Artificial, MIT Press, Cambridge, MA.

Snowden, D.J. and Boone, M.E. (2007), 'A leader's framework for decision making', Harvard Business Review, Vol. 85 No. 11, pp. 68-76.

Sutherland, J. (2015), Scrum: The Art of Doing Twice the Work in Half the Time, RH Business Books, London.

Svahn, F. (2012), Digital Product Innovation: Building Generative Capability through Architectural Frames, PhD thesis, Umeå University, Umeå, Sweden.

Svahn, F. and Henfridsson, O. (2012), 'The dual regimes of digital innovation management', Proceedings of the Annual Hawaii International Conference on System Sciences, Maui, HI, pp. 3347-3356.

Svahn, F., Henfridsson, O. and Yoo, Y. (2009), 'A threesome dance of agency: mangling the socio-materiality of technological regimes in digital innovation', Proceedings of ICIS 2009 – Thirtieth International Conference on Information Systems, Phoenix, AZ, pp. 1–16.

Svahn, F., Lindgren, R. and Mathiassen, L. (2015), 'Applying options thinking to shape generativity in digital innovation: An action research into connected cars', Proceedings of the Annual Hawaii International Conference on System Sciences, IEEE Computer Society, pp. 4141–4150.

Svahn, F., Mathiassen, L., Lindgren, R. and Kane, G. C. (2017), 'Mastering the digital innovation challenge', MIT Sloan Management Review, Vol. 58 No. 3, pp. 14-16.

Svejvig, P. and Andersen, P. (2015), ‘Rethinking project management: A structured literature review with a critical look at the brave new world’, International Journal of Project Management, Vol. 33 No. 2, pp. 278-290.

Takeuchi, H. and Nonaka, I. (1986), ‘The new new product development game’, Harvard Business Review, Vol. 64 No. 1, pp. 137-146.

Vedsmand, T., Cooper, R.G. and Kielgast, S. (2016), Integrating agile with stage-gate® – How new agile-scrum methods lead to faster and better innovation. Retrieved January 2020, from https://innovationmanagement.se/2016/08/09/integrating-agile-with-stage-gate/.

Voss, C., Tsikriktsis. N and Frohlich, M. (2002), ‘Case research: Case research in operations management’, International Journal of Operations & Production Management, Vol. 22 No. 2, pp. 195-219.

Whetten, D.A. (1989), ‘What constitutes a theoretical contribution?’, Academy of Management Review, Vol. 14 No. 4, pp. 490-495.

Wolfenstetter, T., Böhm, M., Krcmar, H. and Bründl, S. (2016), ‘Why product service systems development is special’, in Framinan, J.M., Gonzalez, P. and Artiba, A. (Eds.), Proceedings of the International Conference on Industrial Engineering and Systems Management, IEEE IESM 2015, Institute of Electrical and Electronics Engineers Inc., Seville, Spain, 21-23 October, pp. 1221-1228.

Woodward, M.V. and Mosterman, P.J. (2007), ‘Challenges for embedded software development’, Proceedings of the 50th Midwest Symposium on Circuits and Systems, Montreal, Canada, Vol. 1-3, pp. 524-527.

Yin, R.K. (2009), Case Study Research: Design and Methods, Sage Publication Inc., Thousand Oaks, CA.

Yoo, Y., Boland, J. R., Lyytinen, K. and Majchrzak, A. (2009), ‘Call for papers. Special issue: Organizing for innovation in the digitized world’. Organization Science, Vol. 20 No. 1, pp. 278-279.

Yoo, Y. (2010), ‘Digitalization and innovation’, Working paper, Hitotsubashi University, Institute of Innovation Research, Tokyo, Japan. Retrieved October 2019, from http://hdl.handle.net/10086/18789.

Yoo, Y., Boland, R.J., Lyytinen, K. and Majchrzak, A. (2012), ‘Organizing for innovation in the digitized world’, Organization Science, Vol. 23 No. 5, pp. 1398-1408.

Yoo, Y., Henfridsson, O. and Lyytinen, K. (2010), 'The new organizing logic of digital innovation: An agenda for information systems research', Information Systems Research, Vol. 21 No. 4, pp. 724-735.

Yuan, X., Liu, Y., Kang, L., Sun, Y. and Chen, Y. (2008), 'Adopting CMM in embedded software design and development', Proceedings of the International Conference on Embedded Software and Systems Symposia, Chengdu, China, pp. 50-54.

APPENDICES

Appendix A. Hendler and Boer (2019)

Hendler, S. and Boer, H. (2019), 'Digital-physical product development: a review and research agenda', International Journal of Technology Management, Vol. 80 No. 1-2, p. 12-35, https://doi.org/10.1504/IJTM.2019.099769

Digital-physical product development: a review and research agenda

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Abstract: Companies are increasingly digitally augmenting previously nondigital products. This requires significant changes in the product development process and its supporting context within the companies. However, only little relevant literature exists. The aim of this paper is to develop a platform for further research within this new field by reviewing available literature characterising digital-physical development and proposing a research model and agenda. The paper reveals a scattered and immature field of research.

While digital-physical product development is of huge industrial importance, few papers specifically address the phenomenon and, then, they typically only focus on one or two constructs. So far, we are in the very beginning of theory development. Directions for literature research in adjacent areas are proposed, together with case study and action research methods to explore fitting digital-physical development practices and their context.

Keywords: digital-physical; smart products; new product development; agile development; digital innovation; digitised products; digitalisation.

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Harry Boer is a Professor of Strategy and Organization at the Center for Industrial Production at Aalborg University, Denmark. He holds a BSc in Applied Mathematics and an MSc and PhD both in Management Engineering, all from Twente University, the Netherlands. He has published on subjects such as organisation theory, flexible automation, manufacturing strategy, and continuous improvement/innovation in the International Journal of Operations and Production Management, the Journal of Production Innovation Management, Decision Sciences, the Journal of Manufacturing Technology Management, Creativity and Innovation Management, Production Planning and Control, and the International Journal of Technology Management. His current research interest is in continuous innovation, the effective interaction between day-to-day operations, incremental change, and radical innovation.

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1 Introduction

Embedding digital technologies in customer offerings is not a new phenomenon. The first commercial digital computer with onboard software appeared in the 1950s

(Kubie, 1994). With the growing computer industry other products emerged such as music CD players and digital cameras. More recent examples include smart phones; internet of things (IoT) enabled industrial manufacturing equipment, and toys such as the LEGO®BOOST robot. With the recent technological advancements and competitive pressures, the speed at which companies include digital technology into their offerings is increasing (Broy, 2005; Yoo et al., 2012; Svahn and Henfridsson, 2012; Dawid et al., 2017). Including digital affordances such as programmability, data storage and traceability (Yoo, 2010) into customer offerings can radically alter the price-performance ratio and provide clear competitive advantages (Yoo et al., 2010; Svahn and Henfridsson, 2012), and is therefore often attractive or even necessary for companies to consider.

Augmenting a product by including digital technology in its value proposition may require a manufacturer to radically change its products' lifecycle, architecture, development and post-launch processes, and has proved to be a challenging exercise (e.g., Henfridsson et al., 2014; Svahn et al., 2017a). Porter and Heppelmann (2014, p.98) state: "*[w]hat is under way is perhaps the most substantial change in the manufacturing firm since the Second Industrial Revolution…*" Accordingly, the managerial, process and organisational aspects of how to develop these digital-physical products are of increasing interest (Nambisan et al., 2017; Holmström, 2018).

The two areas of digital and physical product development have evolved relatively independently of each other in practice and in research (Karlsson and Lovén, 2005; Svahn and Henfridsson, 2012) and have resulted in different development practices. Furthermore, literature on embedded software development tends not to focus on combining the two processes, and often takes a more technical angle over a managerial, process or organisational perspective (Haghighatkhah et al., 2017). Although relevant topics such as multi-disciplinarity and systems engineering have been identified in literature on how to develop product-service systems, complex products, cyber-physical systems, hybrid and smart products (e.g., Baines et al., 2007; Wolfenstetter et al., 2016; Bialasiewicz, 2017; Maleki et al., 2017) insight into the question on how to combine physical and digital product development processes is underdeveloped. Similarly, the context within a company that can best support the combined process is unclear, but may need to include features from both software and a manufacturing company (Porter and Heppelmann, 2015). Digital innovation where digital refers to the technology used in either the development process or its outcome, is "…*not yet a fully developed research field, rather it is an emerging body of theory and practice that draws from a number of different social science disciplines*" [Holmström, (2018), p.107].

To emphasise the specific focus of this paper in which digital and physical primarily refers to the innovation outcome, this research uses the term digital-physical product development, where product development is the process of 'transforming ideas into commercial outputs' (Hansen and Birkinshaw, 2007), 'digital' refers to software, and 'physical' to something tangible. The digital-physical output can be described as, e.g., a complex product, a cyber-physical system (typically used within critical system domains with increased reliability and safety requirements (see e.g., Letichevsky et al., 2017) or a product-service system, provided that the process outcome includes both a digital and a physical component. In this paper, the term digital-physical product is used.

Given the underdeveloped field of theory on digital-physical product development coupled with a significant industrial relevance requiring operational theory, the question guiding this research is:

Which development practices and context effectively support the digital-physical development process?

This question is addressed via a literature review, which characterises the process and context of, and clarifies the gaps in knowledge on, the development of digital-physical products from a process, organisational and managerial perspective. A process perspective not only sensitises the research to describe the work that needs to be done in its entirety, but also the individual development practices constituting the combined digital-physical development process. Context refers to the company-internal environment in which the digital-physical product development process takes place, and includes elements such as HR policies, organisation structure and company budgeting processes. Based on the literature review, a model and an agenda for further research are proposed.

The research method is described in Section 2. The findings from the literature review are presented in Section 3 and analysed and discussed in Section 4, where a model and directions for further research are presented. Section 5 concludes the paper.

2 Method

The literature review provides input for further research by uncovering knowledge about the domain, constructs, relationships and explanations (Whetten, 1989) of, in this case, proposed theories on or insight into digital-physical product development. The review includes literature that focuses on digital-physical product development. Literature from adjacent areas such as product-service-system development, complex product development or system development is only included when specific contributions explicitly relate to or include the topic of combining digital and physical product development processes. With an organisational, managerial and process perspective, publications that deal exclusively with how digital-physical products are technically shaped, or present specific tools and techniques, e.g., for making embedded software, are considered out of scope.

The literature search strategy first involved identifying relevant search terms and data sources describing development work. The following search terms were included in all searches: (product development OR product innovation OR software development OR software innovation OR digital innovation). Based on an initial literature exploration, additional search terms were identified to seek out contributions that explicitly relate to or include combining digital and physical product development processes. The first search string included: (software OR agile OR digit*) AND (physical OR tangible OR hardware). A second search string primarily included potential output descriptions of a digital-physical product development process: (product service system OR servitisation OR embedded software OR smart product OR smart object OR intelligent object OR augmented product OR smart service OR digit* OR cyber physical systems). Both search strings were applied to the key words, title, abstract and subject terms of publications in Academic Search Premier and Business Source Premier in EBSCO (a broad representation of business-related journals) and SCOPUS (includes more technically oriented journals in addition to management journals). The returned publications were limited to English language journal articles, conference proceedings, and published theses.

Excluding duplicates, 9,423 publications were sorted based on their titles to ensure relevance. The abstracts of the remaining 723 publications were then considered, leaving 407 publications that were read diagonally. Eventually, 52 publications were identified as important, six of which were found by analysing reference literature. The content analysis forming the basis of this paper was aided by clustering techniques to capture the main themes and specific contributions. Specifically, 498 relevant quotes with additional data such as research topic, industry and key words were identified from the papers. These were sorted into 54 emerging groups based on their content. Individual quotes were represented in multiple groups as needed. Each group was given a headline such as 'complementary planning methods'. These groups were further aggregated into 39 headlines such as 'synergy effects between agile and traditional development tools'. The 39 headlines were further grouped into a final nine findings reported in this paper.

3 Analysis of the literature

Table 1 presents the reviewed literature including the authors, the year, topic, research method, industry when noted, and the focus of the authors in terms of digital development, physical development or a balanced focus on both. Twenty-nine (56%) were published within the latest decade. The 52 publications explore eight topics (Table 2), which shows a scattered body of literature.

Most of the nine final findings from the literature analysis characterising digital-physical development and its context span several of the topics presented in Table 2. These nine findings are explicated below. First, the combined digital-physical product development process is characterised. Next, the differences between digital and physical product development practices and options to combine them are described. Then, the context needed to effectively support the digital-physical development process is presented. Finally, the literature presented in Tables 1 and 2 is analysed in terms of maturity.

Table 1 Presentation of the literature

Author	Year	Topic	Method	Context	Focus
Rauscher and Smith	1995	6	*Experience?*	-	Dig-Phys
Fornaciari and Sciuto	1999	1	Review	-	Dig-Phys
Dagnino	2001	2	*Experience?*	Robotics	Dig-Phys
Durrett et al.	2002	2	Case study	Consumer electronics	Dig-Phys
Kettunen	2003	8	Case study	Telecommunications	Digital
Joglekar and Rosenthal	2003	7	Case study	Healthcare	Dig-Phys
Greene	2004	5	Case study	Consumer electronics	Digital
Broy	2005	1	Case study	Automotive	Digital
Itoh	2005	3	Case study	Automotive, Robotics	Dig-Phys
Karlsson and Lovén	2005	1	Case study	Multiple	Dig-Phys
Rottman	2006	7	Case study	Industrial equipment	Digital
Karlström and Runeson	2006	5	Case study	Telecommunications	Digital
Kettunen	2006	1	Review	Telecommunications	Digital
Broy et al.	2007	1	*Review?*	Automotive	Dig-Phys
Cordeiro et al.	2007	5	Case study	Healthcare	Digital
Woodward and Mosterman	2007	1	Conceptual	Consumer electronics	Digital
Andreasson and Henfridsson	2008	3	Case study	Automotive	Dig-Phys
Cordeiro et al.	2008	5	Case study	Healthcare	Digital
Rottier and Rodrigues	2008	5	Case study	Healthcare	Digital
Yuan et al.	2008	2	Case study	-	Dig-Phys
Diegel et al.	2008	6	Case study	Healthcare	Dig-Phys
Evans	2009	2	Conceptual	Automotive	Dig-Phys
Svahn et al.	2009	3	Case study	Automotive	Dig-Phys
Yoo et al.	2010	3	Conceptual	-	Dig-Phys
Huang et al.	2012a	5	Case study	Satellite	Dig-Phys
Huang et al.	2012b	5	Case study	Satellite	Dig-Phys
Eklund and Bosch	2012a	5	Case study	Automotive	Digital
Eklund and Bosch	2012b	2	Conceptual	Automotive	Dig-Phys
Lee and Berente	2012	3	Quantitative	*Automotive*	Dig-Phys

Svahn and Henfridsson	2012	4	Review	-	Dig-Phys
Yoo et al.	2012	4	Conceptual	-	Dig-Phys
Svahn	2012	3	Case study	Automotive	Dig-Phys
Henfridsson et al.	2014	3	Case study	Automotive	Dig-Phys
Katumba and Knauss	2014	5	Case study	Automotive	Dig-Phys
Eklund et al.	2014	5	Case study	Healthcare	Dig-Phys
Porter and Heppelmann	2014	4	Conceptual	Multiple	Dig-Phys
Lerch and Gotsch	2015	3	Case study	-	Dig-Phys
Nylén and Holmström	2015	4	Conceptual	-	Dig-Phys
Porter and Heppelmann	2015	1	Conceptual	Multiple	Physical
Svahn et al.	2015	4	Action Research	Automotive	Dig-Phys
Abrell et al.	2016	1	Case study	Heavy B2B manufacturing industry	Physical
Cooper	2016	5	Case study	Automotive, Consumer electronics	Physical
Martini et al.	2016	6	Case study	Automotive, Telecommunications	Digital
Könnölä et al.	2016	5	Case study	Telecommunications, various B2B equipment	Physical
Lwakatare et al.	2016	5	Case study	-	Dig-Phys
Dawid et al.	2017	4	Conceptual	B2C	Physical
Eklund and Berger	2017	5	Case study	-	Dig-Phys
Svahn et al.	2017a	4	Case study	Automotive	Dig-Phys
Svahn et al.	2017b	4	Case study	Automotive	Dig-Phys
Henfridsson et al.	2018	3	Conceptual	Consumer electronics	Dig-Phys
Holmström	2018	3	Conceptual	-	Dig-Phys
Mocker and Fonstad	2018	2	Case study	Automotive	Dig-Phys

Table 2 Key topics

	Paper topics	No. of papers
1	Specific and detailed process challenges in the product development process	8
2	High level process and contextual design changes needed	6
3	Product conceptualisation/architecture and its implications on the practices/capabilities of companies	10
4	The specific nature of digital technology and its implications on the practices/capabilities of companies	8
5	Application of agile software methods that either interfaces with non-agile, concurrent physical product development or includes it	14
6	Reduction of time-to-market	3
7	Successful outsourcing of software development	2
8	Knowledge management	1

3.1 The characteristics of the digital-physical product development process

"*With the objective of integrating software in basically mechanical products several activities create problems for the traditionally mechanical company. They meet many problems for which there are no known solutions …*" [Karlsson and Lovén, (2005), p.346]. Developing software and embedded software is a complex exercise (e.g., Fornaciari and Sciuto, 1999; Broy et al., 2007; Andreasson and Henfridsson, 2008; Katumba and Knauss, 2014; Svahn et al., 2017a). Furthermore, according to Broy's (2005) studies in the automotive industry, the challenges related to combining software development with physical product development have increased in number and complexity with the increasing amount of developed software per product.

Some of these challenges include more complex specifications (e.g., Durrett et al., 2002; Kettunen, 2003; Katumba and Knauss, 2014) and trade-off decisions (e.g., Rauscher and Smith, 1995; Karlsson and Lovén, 2005; Eklund et al., 2014) and increased risk of errors (e.g., Rottman, 2006; Woodward and Mosterman, 2007; Yuan et al., 2008). In addition, Eklund and Berger (2017) note how the digital-physical development process becomes more challenging due to the many digital-physical interdependencies. Dawid et al. (2017) highlight how smart products require a higher level of multi-disciplinarity and collaboration with companies from yet unrelated industries.

With the digital-physical product development process being relatively more complex, interdependent and diverse in terms of the technologies and competences needed (Andreasson and Henfridsson, 2008), it inherently becomes more unpredictable (cf. Boer, 1991; Boer and During, 2001). Dawid et al. (2017) argue that the high degree of innovativeness stemming from smart products compromises the ability of companies to use existing market analysis tools to predict consumer preferences.

In addition to these challenging process characteristics, Yoo et al. (2010) address the re-programmability of the digital immateriality as an unbounded mix and match capability resulting in rapid innovation of digital products and with relatively low investment, making it inexpensive to compete for customer attention (Svahn and Henfridsson, 2012). The resulting generativity is also rooted in the product architecture of a digital-physical product: "*The layered modular architecture is a hybrid between a modular architecture* [from physical products] *and a layered architecture* [from software] *... Generativity ... is accomplished through loose couplings across layers whereby innovations can spring up independently*" [Yoo et al., (2010), p.728]. The layered modular architecture is further elaborated on by Henfridsson et al. (2018) as the basis of an early theory of digital-physical product development (Holmström, 2018).

The mixed materiality of digital-physical product development resulting in new product architectures and its more challenging process characteristics (uncertainty, complexity, interdependence and diversity) require several new practices. Authors see a need for product development approaches such as horizontal innovation and combinatorial innovation (Yoo et al., 2012), promoting product variations and embracing complementary products (Svahn et al., 2015), distributed innovation (Yoo et al., 2010), system interoperability (Porter and Heppelmann, 2015), and thinking across physical components that allow for a better exploitation of the software medium (Lee and Berente, 2012). Additionally, digital-physical product development requires designing for continued product enhancement after launch (Broy, 2005; Yoo et al., 2012; Porter and Heppelmann, 2015; Eklund and Berger, 2017), designing for security and big data (Porter and Heppelmann, 2015), and adopting new methods for extracting tacit user knowledge (Abrell et al., 2016).

Finding 1: Challenging process characteristics require new practices

Digital-physical product development is characterised by a mixed materiality and a high degree of complexity, diversity, interdependence and uncertainty, which requires manufacturers to rethink existing, and develop new, product development practices.

3.2 Two sets of separate and different practices

Adding to the above overall characterisation, digital-physical product development is predominantly described as two separate processes and development teams that work in parallel with their own development practices, but coordinate their efforts (Joglekar and Rosenthal, 2003; Broy, 2005; Broy et al., 2007; Woodward and Mosterman, 2007; Cordeiro et al., 2008; Katumba and Knauss, 2014; Lerch and Gotsch, 2015; Lwakatare et al., 2016). This, however, is problematic as Rauscher and Smith (1995, p.186) note: "*Despite the current focus on concurrent engineering and cross-functional teams, software engineering is often poorly integrated with the rest of the product development effort. The result is usually a costly delay in the product's introduction to the market*". Only in a few case studies is it reported how the software and the physical product development processes are fully or partly facilitated using the same overall development practice, i.e., an agile development practice (Huang et al., 2012a, 2012b; Könnölä et al., 2016; Eklund and Berger, 2017) or an agile-stage-gate model (Cooper, 2016), albeit with mixed results. None of the authors compare the different scenarios.

Finding 2: Separate and different practices.

Digital-physical product development predominantly involves separate and different digital and physical development practices and organisations.

3.3 The different development practices

The literature emphasises several dissimilar digital and physical development practices that become apparent when combining them in digital-physical product development (Table 3).

Physical product development assumes 'first-time-through' due to a relatively long-term market and technology predictability (Svahn, 2012; Svahn and Henfridsson, 2012). Furthermore, the typical high cost of manufacturing processes fosters a focus on the reuse of existing assets through product platforms, dominant designs and incremental over radical product development as well as an awareness of the consumption of scarce resources (Svahn, 2012; Svahn and Henfridsson, 2012). This enables and motivates a fine-tuned, plan-driven approach with clear phases from idea to launch (Cooper, 2016). Focus is on minimising variation early on via an early specification lock (early binding) with subsequent risk and deviation management (Svahn and Henfridsson, 2012; Eklund and Berger, 2017). Assuming high predictability in process outcomes and market demands, coupled with a relative process predictability, physical development processes are often coordinated by one long, linear development cycle with few prototype spirals (e.g., Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund et al., 2014; Lwakatare et al., 2016).

Table 3 Dissimilar development practices

Physical product development	Digital product development	Key references
One long development cycle (years) with few prototype iterations (months) typically governed by a linear staged and gated model	Many short iteration cycles (weeks) using agile development methods with frequent releases	Joglekar and Rosenthal (2003), Karlström and Runeson (2006), Cordeiro et al. (2007), Rottier and Rodrigues (2008), Svahn et al. (2009), Eklund and Bosch (2012b), Eklund et al. (2014), Henfridsson et al. (2014), Lwakatare et al. (2016), Könnölä et al. (2016), Abrell et al. (2016), Eklund and Berger (2017), Mocker and Fonstad (2018)
Early binding: extensive up front planning with early specification lock assuming long term predictability	Late binding: evolvement of requirements throughout development assuming poor long term predictability	Dagnino (2001), Kettunen (2003), Karlström and Runeson (2006), Svahn and Henfridsson (2012), Svahn (2012), Eklund et al. (2014), Henfridsson et al. (2014), Lwakatare et al. (2016), Könnölä et al. (2016), Abrell et al. (2016), Eklund and Berger (2017), Svahn et al. (2017a, 2017b)
Detailed information needed later in the process	Detailed information needed already early in the development	Karlström and Runeson (2006)
Limited user involvement	Extensive user involvement	Joglekar and Rosenthal (2003), Lwakatare et al. (2016), Abrell et al. (2016)
Product development project stops after launch	Product development continues after initial launch until end of product life	Dagnino (2001), Yoo et al. (2010) Porter and Heppelmann (2015) Mocker and Fonstad (2018)
Focus on minimising variation via planning and deviation management	Focus on exploiting variation via frequent transparency based decision-making and flexible scope	Huang et al. (2012b)
Key process performance measures: time to market; reduction in inventory costs; manufacturability	Key process performance measures: development costs	Joglekar and Rosenthal (2003)
Optimise for exploitation, stability and some flexibility	Optimise for exploration and agility	Svahn and Henfridsson (2012), Svahn (2012), Könnölä et al. (2016)

Tools, language and norms adapted to physical product development	Tools, language and norms adapted to digital product development	Karlsson and Lovén (2005), Yoo et al. (2012), Lee and Berente (2012), Eklund et al. (2014), Porter and Heppelmann (2015), Cooper (2016), Mocker and Fonstad (2018)
Budget and time is flexible	Scope is flexible	Cooper (2016)
Firm-centric development	External orientation with distributed development	Joglekar and Rosenthal (2003), Yoo et al. (2010), Yoo et al. (2012), Svahn and Henfridsson (2012), Svahn (2012), Svahn et al. (2015), Svahn et al. (2017a)
Medium need for process structure and clear completion points	High need for process structure and clear completion points	Rauscher and Smith (1995)
Marginal and fixed costs	Limited fixed costs	Svahn and Henfridsson (2012), Svahn (2012)
Soft factors contribute less to project success	Soft factors contribute greatly to project success	Kettunen (2003)
Development is predominantly organised in component teams without end-to-end visibility of the value stream	Development is predominantly organised in cross-functional feature teams	Andreasson and Henfridsson (2008), Svahn et al. (2009), Lwakatare et al. (2016), Könnölä et al. (2016), Mocker and Fonstad (2018)

In contrast, the difficulty of developing the right product for software consumers in a dynamic market with infinite possibilities has resulted in agile development practices, which assume that customer needs are discovered over time (Karlström and Runeson, 2006; Svahn and Henfridsson, 2012; Eklund and Bosch, 2012b; Eklund et al., 2014; Lwakatare et al., 2016; Mocker and Fonstad, 2018). These agile practices enable the ability to frequently adapt to new learning in multiple, short iterative development cycles, each resulting in potentially shippable products. Once enough development cycles have been performed to provide sufficient customer value, the product is released and enhanced after release (Schwaber and Beedle, 2001; Cohn, 2010). This focus on exploration and adaptability is in great contrast to the exploitation and stability optimised physical development process.

The short iterative development cycles are greatly aided by the re-programmability of software (Yoo, 2010), which does not require manipulation of tangible assets (Könnölä et al., 2016; Eklund and Berger, 2017), i.e., no long lead times for prototyping models or development of new manufacturing tooling or transport. In contrast to digital development, the manufacturing capability causes significant fixed and marginal costs associated with every unit produced (Svahn, 2012; Svahn and

Henfridsson, 2012). This causes the cost of product iterations to be higher compared to software and involves a focus on unit cost reduction in addition to manufacturability (Joglekar and Rosenthal, 2003; Broy et al., 2007; Svahn, 2012). In contrast the primary cost in digital development is the development hours (Joglekar and Rosenthal, 2003; Svahn, 2012).

Another key difference is emphasised by Cooper (2016), who highlights a floating scope as a core agile practice, i.e., a continuous adjustment of product features to new information while keeping resources and schedule constant (Schwaber and Beedle, 2001; Cohn, 2010). In contrast, physical product development favours schedule and resource adjustments (Svahn and Henfridsson, 2012; Cooper, 2016). Such differences between the two methods coupled with differences in tools, such as planning methods (Karlström and Runeson, 2006) and the dissimilar output materiality, results in disparate norms and languages (Karlsson and Lovén, 2005; Yoo et al., 2012; Lee and Berente, 2012; Eklund et al., 2014; Porter and Heppelmann, 2015; Cooper, 2016; Mocker and Fonstad, 2018). Mocker and Fonstad (2018, p.10) give an example describing challenges when digital and physical competences work cross-functionally: "*We had to work on better understanding each other. For example, it took us one-and-a-half years and a lot of discussions to get clarity on three simple words: portal, platform, profile*".

Yet another difference in practice is summarised by Svahn and Henfridsson (2012, p.3349): "… the firm-centric view is largely shifted out. *Technological* [IT] *progression is not seen as a phenomenon deriving from linear development processes, hierarchical organisations, and vertical industry structures. Instead, IT innovation research underlines that digital technology destroys many barriers favouring incumbent innovation. Over time this cultivates boundary-spanning practices … As a result, innovation translates into a distributed activity…*"

In addition to unpredictability and materiality requiring different practices, differences in product architectures also requires different practices. Several authors mention how physical product development is predominantly organised into functionally specialised component teams to efficiently organise the development of various components in a modular architecture (Andreasson and Henfridsson, 2008; Svahn et al., 2009), whereas digital product architectures to a higher extent requires cross-functionality to be able to deliver complete user functionality (Lwakatare et al., 2016; Könnölä et al., 2016; Mocker and Fonstad, 2018). Authors explain this relationship using Baldwin's (2008) mirroring hypothesis (Andreasson and Henfridsson, 2008; Svahn et al., 2009; Lee and Berente, 2012; Henfridsson et al., 2014; Svahn et al., 2015), predicting that organisational ties within a project, firm, or group of firms will correspond to the technical dependencies in the development process.

Hence, the authors observe the dissimilar practices when combining them in digital-physical product development and offer explanations predominantly related to the different materiality, different levels of uncertainty and different product architectures. Svahn et al., (2015, p.4124) conclude: "[incumbent firms] *need to develop entirely new sets of capabilities to resolve contradictions between digital innovation and product innovation*".

Finding 3 Adaptability vs. stability optimised practices.

Physical and digital development deploys significantly different practices that are predominantly explained by differences in uncertainty, materiality and product architecture. Digital development is optimised for fast feature delivery, effective exploration and fast adaptation using agile development methods with late binding. Physical development is optimised for efficient component development, stable exploitation of existing investments, manufacturability and unit cost while coping with long lead time processes using a firm-centric, linear development process with early binding.

3.4 Alignment of digital and physical product development practices

The long-term, plan-driven, staged and gated approach that is typically used by physical product development is used as the primary coordination mechanism combining all the needed development streams, including software development (Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund and Bosch, 2012b; Eklund et al., 2014; Lwakatare et al., 2016). This imposes an early and extensive planning phase upon the software development process, with early binding of many design decisions and challenging dependencies. This challenges the agile software development practices, which are designed to optimise for late binding, short-term planning, and fast change. Karlström and Runeson (2006, p.216) note: "*The gate models are too inflexible to accommodate software development in any form*". Eklund and Berger (2017, p.173) explain: "*…individual* [software] *teams are able to reprioritise and implement software features in a 2-4 weeks cycle, i.e., are agile, while the overall R&D process is typically still governed by an overarching stage-gate or V-model …. Thus, software deliveries were typically planned in time towards pre-scheduled integration points that are determined by mechanics and manufacturing development. As a result the benefits typically associated with agile development like short lead-times in launching new or updated products were not perceived by developers*".

Other difficulties relate to the detailed level of technical information needed early in software development but later in physical product development (Karlström and Runeson, 2006). Furthermore, the software can already be "old" before release if its development has been aligned with the longer physical development cycle (Eklund and Bosch, 2012b). Hence, in other cases, software development does not start until a mechanical concept has been locked, which limits an exploitation of software affordances in the final product, such as integrating functionalities across product component boundaries using digital technology (Karlström and Runeson, 2006; Diegel et al., 2008; Yuan et al., 2008; Evans, 2009; Eklund et al., 2014). Evans (2009, p.16) states: "*The reality is that the core [software] design functionality is being held back by the pre-determined hardware platform, and changing it would cause a significant delay".* So, Evans (2009) and other authors (e.g., Diegel et al., 2008; Eklund and Bosch, 2012b) reporting from automotive and healthcare industries suggest that adapting software development to the physical development practices results in reduced product performance. However, the authors report that, in practice, software development tends to adapt to the physical product development by, e.g., planning of work including early binding, preparing the required stage-gate related documentation, and adapting to governance structures and role descriptions (Joglekar and Rosenthal, 2003; Karlström and Runeson, 2006; Rottier and Rodrigues, 2008; Eklund and Bosch, 2012b; Eklund et al., 2014; Cooper, 2016).

Finding 4 The digital development practices tend to adapt to the physical development practices.

Differences between digital and physical development complicate successful combination and it is often the software development practices that adapts to the requirements of the physical development practices.

3.5 Positive effects from combining

As established above, combining the two types of processes poses challenges and except for Cooper (2016), who proposes an agile stage-gate hybrid, but does not explore the details of combining agile and stage-gate, only few authors mention positive process effects. Karlström and Runeson (2006, p.221) describe positive effects obtained from combining agile micro planning with macro planning from the stage-gate development methods: "*Well functioning micro-planning seems to lead to better adherence to the macro-plans…*". Additionally, agile development methods used in software development can help mitigate risks and errors in the physical product development process (Joglekar and Rosenthal, 2003; Rottier and Rodrigues, 2008; Greene, 2004): "*…software is more flexible than hardware; it seems easier to change. Thus, product development planners usually allow for some software additions or changes late in a product development cycle to correct hardware problems or add new functionality*" [Rauscher and Smith, (1995), p.189]. For example, software can compensate for a physical design error, such as an unwanted variability in a sensor reading, by changing some code at a lower cost. Additionally, short software development cycles can help uncover physical design flaws early due to, e.g., early integration tests with crude physical mock-ups. Joglekar and Rosenthal (2003, p.382) describe from the healthcare industry: "*…software reviews by the MedDev management were much more frequent than their traditional gates because of the shorter development cycle for software".*

Finding 5 Digital development practices help mitigate physical process uncertainty

Despite differences in practices complicating their successful combination, some authors observe that the digital immateriality and development practices complement the physical product development practices by mitigating some uncertainty.

3.6 Traditional versus agile product development practices

Several authors advocate making the physical product development practices more agile, which would reduce the differences between the two sets of practices and allow for a more successful coordination and integration (Cooper, 2016). It would also enable the physical product to more easily evolve in alignment with new learning (Huang et al., 2012b) and even allow for a process in which software design decisions drive physical product design decisions, leading to the software driven digital-physical product development process proposed by Evans (2009).

While Huang et al. (2012a, 2012b) and Cooper (2016) report successful use of agile development practices for digital-physical product development, other authors, notably Könnölä et al. (2016) and Eklund and Berger (2017), report challenges. Some challenges concern team composition (Könnölä et al., 2016; Eklund and Berger, 2017) and task management flow (Könnölä et al., 2016); others relate to physical cycle times being longer than digital ones, making it difficult to find an optimal coordination frequency (Könnölä et al., 2016). Some reasons reported for the slower physical development cycles include long field tests (Könnölä et al., 2016), and a slower functional organisation in terms of coordination speed (Eklund and Berger, 2017).

Könnölä et al. (2016) and Eklund and Berger (2017) suggest a number of practices to help solve these challenges such as fully cross-functional team compositions (Könnölä et al., 2016; Eklund and Berger, 2017), involving the whole organisation in agile practices to gain system benefits (Könnölä et al., 2016), using platform development to help speed up physical development cycles, reducing the interdependencies between digital and physical, and accepting a speed loss in software development to be able to align that process with the physical process cycle times (Eklund and Berger, 2017).

Karlström and Runeson (2006) and Eklund and Bosch (2012b) suggest accepting a gradual growth of requirements, and Eklund and Berger (2017) mention the importance of accepting incomplete components for the digital-physical prototypes.

So most of the literature reports examples of the digital-physical product development process being governed by different development practices. Nevertheless, some authors propose using agile practices for both processes. However, the possibilities for, and consequences of, aligning the development methods within digital-physical product development are not yet well understood and need further exploration.

Finding 6 Scarcity of literature on combination practices and their effects

Some literature advocates making the physical product development practices more agile. However, there is a scarcity of literature investigating this possibility or proposing other mechanisms to combine or reconcile the two processes, and their effects on the overall process.

3.7 Differentiation instead of integration

Some authors explicitly argue for the benefits of keeping the two processes separate in order to avoid software development being forced to adhere to early physical product development decisions (Dagnino, 2001; Yuan et al., 2008; Evans, 2009). Evans (2009) also suggests a software driven digital-physical product development process, which supports the notion that the competitive advantage of digital-physical products increasingly comes from software [Evans, (2009), p.9]: "*Where the value of design lies, and where the prime focus of design effort should lie, is in the soft elements of a design that define its competitive advantage".* This encourages a development process that focuses on developing software largely independently from the hardware (Cordeiro et al., 2008). Evans (2009, p.17) note from a digital viewpoint: "*The hardware platform is not a prime consideration and can be dealt with later, when the product's form and function have been developed to a mature state*". This can also prevent the situation where issues are solved in software that was better solved in hardware (Eklund et al., 2014). Digital platforms (Itoh, 2005) and digital-physical product architectures (Yoo et al., 2010) are developing, which help to separate physical and software development. Martini et al. (2016) conclude that digital-physical product development requires a balance of boundary spanning activities; currently, however, there is no theory on the right balance. "*…when a number of different processes mismatch but need to interact, there is a need for more spanning activities and coordinators*" (p.22). "*The actual amount of time spent in interaction is not known and the spanning activities need to be limited in order to allow the* [software] *team to focus. Such topic, in our opinion, requires further research*" (p.21).

Finding 7 Scarcity of literature on balancing integration and differentiation

Literature does not provide clear guidelines for balancing the levels of integration and differentiation between software and physical product development in a digital-physical product development process.

3.8 The product development context

When digitally augmenting its products, a manufacturer not only needs to adapt its product development process, but also the context supporting the process (Andreasson and Henfridsson, 2008; Svahn and Henfridsson, 2012; Porter and Heppelmann, 2014; Yoo et al., 2010, 2012, Svahn et al., 2015). Specifically, Porter and Heppelmann (2014) encourage manufacturing companies to focus on differentiation and tailoring strategies, broadening the value proposition and becoming part of broader product systems. The new strategic choices can result in new business models such as selling products-as-a-service and relying on big data for competitive advantage (Porter and Heppelmann, 2015; Yoo et al., 2010, 2012; Dawid et al., 2017).

In addition to a change of strategy, organisational adaptations are needed (Joglekar and Rosenthal, 2003; Broy et al., 2007; Katumba and Knauss, 2014). Porter and Heppelmann (2015) state the need to complement the manufacturer's organisational structure with various new business functions, including tighter collaboration between IT and R&D. Svahn et al. (2015) describe how Volvo formed an app development department, an app board, a user experience steering group and a new transitional hub to host new competences, and created new needed lateral linkages between existing functions.

Furthermore, the work performed in many functions such as logistics and maintenance (Broy et al., 2007; Porter and Heppelmann, 2015), IT (Yoo et al., 2010), manufacturing, marketing (Porter and Heppelmann, 2015; Dawid et al., 2017), pricing (Dawid et al., 2017), and after-sales service (Porter and Heppelmann, 2015) will need to change, too. Software maintenance requires new business processes such as version and configuration control, software updates, and tracing and diagnosis (Broy, 2005). Developing digital-physical products also implies different cultural norms, working styles, terminology and different frames of reference (Kettunen, 2003; Karlsson and Lovén, 2005; Porter and Heppelmann, 2015). Importantly, Svahn et al. (2017a, p.239) find: "*Firms must develop new capabilities without jeopardising existing product innovation practices*".

Finding 8 Scarcity of literature on a fitting development context

The literature suggests that the product development context within a traditional manufacturer, including its strategy, organisational arrangements, culture, processes outside the product development function, and its business model, is not able to successfully support, and needs to be adapted to, the requirements of digital-physical product development. However, although several bits and pieces have been proposed, only little operational insight exists into the changes required.

3.9 Maturity of the body of literature

Christensen (2006) suggests that theory is built in two major stages: the descriptive and the normative stage. Each proceeds through three steps: observation, categorisation and association. This review clearly shows that the digital-physical development phenomenon does exist and is increasingly relevant to manufacturing companies. However, in terms of Christensen's model, research on digital-physical development is merely in the very beginning of descriptive theory building: researchers primarily observe the phenomenon and describe and measure what they see from various viewpoints. Though authors have pointed out that established manufacturers experience a significant challenge when digitalising (e.g., Andreasson and Henfridsson, 2008; Svahn et al., 2017a) only eleven (21%) of the papers are written with the manufacturer in focus (Table 1). The literature is scattered across diverse topics (Table 2) and thirty-three (63%) of the papers are not building upon previous work on the topic. A coherent body of literature is just starting to emerge.

Thirty-six (69%) of the papers present case evidence (Table 1) and none of them test theory on digital-physical product development. Furthermore, most research is based on incumbent, medium to large companies operating both within B2B and B2C with established product development practices for physical products and various degrees of maturity of software development practices. At least ten of the papers (Table 1) represent an empirical context from the automotive industry from predominantly the same group of researchers, and no apparent examples from young industries or start-ups exist.

The literature does not provide coherent or operational theory on how to effectively develop digital-physical products, nor on a context (strategy, organisational arrangements, culture, processes outside the product development functions, business model) that can effectively support this process. Finally, the literature is predominantly tacit about the capability (cf. e.g., Cohen and Levinthal, 1990) of organisations to find and absorb the right practices.

Finding 9 Theory on development practices, context and the capability to provide the right practices and context is emerging but scattered and immature

Literature on digital-physical product development is emerging but the set of topics addressed is highly scattered and incomplete. There is no coherent body of theory on

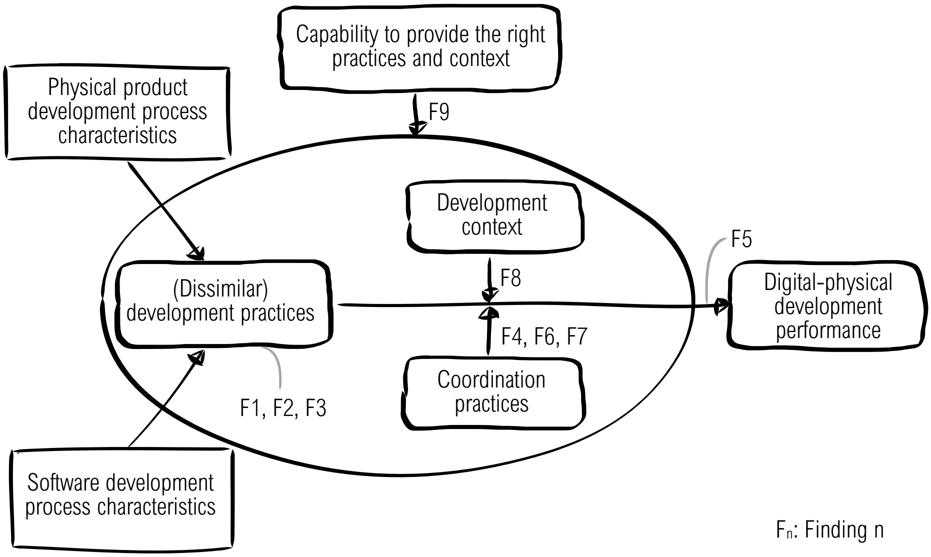
1. the practices and context required to effectively combine digital and physical product development
2. the capability to find and, then, implement these practices and their context effectively.

4 Further research

4.1 Towards a research model

The reviewed literature provides a description of digital-physical development from a process perspective. Although the literature is scarce and scattered, a model and several key constructs and relationships are emerging to help develop further research of digital-physical product development from a process perspective. Figure 1 proposes a research model and positions the findings relative to each other.

First, the model includes a set of *development practices*, which are likely to be *dissimilar* due to the differences between the software development and the physical product development *process characteristics*. Hence, a key contribution from the literature review involves understanding the phenomenon in terms of two separate and dissimilar development processes. One optimised for stable exploitation of existing investments and the other optimised for adaptability. This results in different information needs at different points in time, different work organisations, and different competences (findings 2 and 7). Furthermore, the characteristics of the combined process inferred from the literature involve a mixed materiality and a relatively high degree of complexity, diversity, interdependence and uncertainty. This requires the manufacturer to rethink existing, and develop new, product development practices and processes, and confirms the importance of this research field(finding 1).



Finding 1: Challenging process characteristics require new practices
Finding 2: Separate and different practices
Finding 3: Adaptability vs. stability optimised practices
Finding 4: The digital development practices tend to adapt to the physical development practices
Finding 5: Digital development practices help mitigate physical process uncertainty
Finding 6: Scarcity of literature on combination practices and their effects
Finding 7: Scarcity of literature on balancing integration and differentiation
Finding 8: Scarcity of literature on a fitting development context
Finding 9: Theory on development practices, context and the capability to provide the right practices and context is emerging but scattered and immature

Figure 1 Research model

Combining the two dissimilar processes without taking any further action in terms of aligning, coordinating or even integrating them has been reported to produce negative (finding 4) but also positive (finding 5) development performance effects. The performance effects caused by the combination may be moderated by *coordination practices*[1] (findings 4, 6 and 7) such as fully cross-functional team compositions (Könnölä et al., 2016) or planning the work within the software development process to match a traditional stage-gate model (Karlström and Runeson, 2006; Eklund and Bosch, 2012b). Therefore, understanding digital-physical product development in terms of dissimilar practices and their performance effects enables the innovation manager to optimise the full process system. Reflecting this, the research model depicts that the two processes can be combined using coordination practices that moderate the relationships between the *dissimilar development practices* and the overall *digital-physical development performance*, expressed in terms such as development productivity, lead time, and product competitiveness in terms of quality, cost and performance (Kuwashima and Fujimoto, 2013).

Similarly, the context in which the development process takes place (strategy, organisational arrangements, culture, processes outside the product development functions, business model) may also moderate the relationship between the digital-physical development process and its performance (finding 8). This has implications, not only for the innovation manager, but also for the other functions in the company such as purchasing and IT. Examples of a supportive development context include features such as flexible manufacturing, supply chain operations (Dawid et al., 2017) and the development and management of relevant portfolio strategies (Porter and Heppelmann, 2014) (finding 8).

A final key issue concerns the capability (finding 9) of the manufacturer and potential partners to *provide the right practices and context* that fit the process characteristics of the combined digital-physical product development process (finding 1). In addition to the coordination practices (findings 4, 6 and 7), these practices involve the ones used within each of the development processes (findings 1 and 3). Examples of digital-physical development practices are designing for continued product enhancement after initial launch and big data collection (e.g., Porter and Heppelmann, 2015).

4.2 Objectives and questions for further research

This research model is intended to be instrumental in research on the possibilities to combine physical and digital product development effectively. It answers the recent calls for theory development for this new field from Nambisan et al. (2017) and Holmström (2018) and offers a process perspective on the phenomenon. The model outlines three key areas for further research, namely research aimed at identifying:

1. Practices that allow digital and physical product development processes to be coordinated effectively (findings 2 to 7).

2. Product development practices and context which best fit the characteristics of digital-physical product development (findings 1 and 8).
3. The capability to find and implement these practices and a suitable overall development context (finding 9).

Elaborating on the first research area, no clear theory exists on how to combine the two different processes (finding 9) while being sensitive to their differences and optimising the full process system. This raises several related questions:

1. Are there any practices that help align the physical and the software development process effectively, without compromising the performance of either of the two processes?
2. Is it perhaps more effective to optimise each of the two processes separately, and take the performance impact from the misfit between the processes for granted?
3. Or is the most effective solution to sub-optimise one, or both, processes by, for example:
    a. Making the physical product development process more agile?
    b. Making the software development less agile?
    c. Changing the practices in both processes?

In view of the recent trend within agile development methods for physical product development (e.g., Sommer et al., 2015; Cooper, 2016), more companies can be expected to experiment with the scenarios pointed at in questions c1 and c3. Further research should therefore initially focus on these scenarios and their performance effects.

While most of the findings consider the challenges involved with digital-physical product development, a few complementary practices are identified (finding 5). Hence, when understanding the performance effects of combining two different practices, potential positive process effects should also be explored.

The level of integration and differentiation between the two processes is also an interesting aspect (finding 7):

4. Are the negative performance effects in projects with a high level of interdependency between digital and physical practices greater than the positive effects, so that effort should be put into significantly reducing the interdependencies via, e.g., the product architecture or platform development?

This would allow the digital and physical development processes to run relatively separately. Research is needed exploring the impact of product architecture/platform on the required level of integration and build on the digital-physical architectural works from Yoo et al. (2010) and Henfridsson et al. (2018).

The second research area outlined above is concerned with exploring the characteristics of the overall digital-physical product development process and identifying fitting development practices and a development context within the company that can best support the process. The literature review revealed several development practices in relation to Finding 1, such as horizontal and combinatorial innovation (Yoo et al., 2012), which may be more fitting to digital-physical product development. Finding 8 establishes a need to further research the impact of organisational context, which may play a role in supporting digital-physical product development.

The third research area focuses on the capability, comparable to absorptive capacity (e.g., Cohen and Levinthal, 1990), not only to identify but also to implement the necessary development practices and create a suitable context, and to learn from previous experiences for future development projects.

4.3 Research design options

First, the constructs embedded in the model must be further operationalised. Because of the lack of existing theory within digital-physical product development organisation, operations management and innovation theory are expected to provide important insight to do so. Specifically, an area such as product-service systems development is concerned with relevant topics such as design for product evolvement after launch, process interdependencies, multi-disciplinarity, systems engineering and life-cycle costs (e.g., Wolfenstetter et al., 2016; Maleki et al., 2017).

Then, as to the design of the research proposed here, larger-scale studies, including surveys, are not currently the most obvious research approach due to the relative immaturity of the field, which is in the stage of descriptive theory development (cf. Christensen, 2006). However, with the current acceleration of the spread of digitalisation in industry, opportunities are growing for researchers to develop theory using case studies (Caniato et al., 2018) and perhaps even test some of it with action research, while solving problems for manufacturing companies within a rapidly evolving field.

5 Conclusions

Aimed at contributing to theory development within a new field, this paper clarifies a gap in knowledge and characterises the process and context for development of digitally enhanced products using several empirically illustrated findings from a process, organisational, and managerial perspective.

Digital-physical product development involves two separate processes and different development methods, which need to be combined. In practice, the digital development process is often adapted to the physical product development process. The question is if this is the most effective solution. At least two other scenarios may be feasible. However, given the current state-of-the-theory, it is not possible to confirm which integration scenario is best.

A research model and agenda are proposed to shed light on the digital-physical product development process, its characteristics, practices, context, and options to combine the two sub-processes effectively. In view of the relative lack of theory, it is proposed to use adjacent areas of literature as well as case study and action research to further operationalise and test propositions.

References

Abrell, T., Pihlajamaa, M., Kanto, L., Brocke, J. and Uebernickel, F. (2016), 'The role of users and customers in digital innovation: Insights from B2B manufacturing firms', Information and Management, Vol. 53 No 3, pp. 324–335.

Andreasson, L. and Henfridsson, O. (2008), 'Digital differentiation, software product lines, and the challenge of isomorphism in innovation: a case study' in ECIS 2009: Proceedings of the European Conference on Information systems, pp. 3027–3039.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M. and Wilson, H. (2007), 'State-of-the-art in product-service systems', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 221 No 10, pp. 1543–1552.

Baldwin, C.Y. (2008), 'Where do transactions come from? Modularity, transactions, and the boundaries of firms', Industrial and Corporate Change, Vol. 17 No 1, pp. 155–195.

Bialasiewicz, J.T. (2017), 'Interaction of concurrent processes in cyber-physical systems', Proceedings of the 14th IEEE International Conference on Industrial Informatics, Polish-Japanese Academy of Information Technology, Warsaw, Poland, pp. 516–521.

Boer, H. (1991), Organising Innovative Manufacturing Systems, Gower, Aldershot.

Boer, H. and During, W.E. (2001), 'Innovation. What innovation? A comparison between product, process and organisational innovation', International Journal of Technology Management, Vol. 22 Nos. 1–3, pp. 83–107.

Boer, H., Kuhn, J. and Gertsen, F. (2006), 'Continuous Innovation: Managing Dualities through Co-ordination', CINet Working Paper Series, pp.1–15.

Broy, M. (2005), 'Automotive software and systems engineering', Proceedings of the Third ACM and IEEE International Conference on Formal Methods and Models for Co-design, Verona, Italy, pp. 143–149.

Broy, M., Krüger, I.H., Pretschner, A. and Salzmann, C. (2007), 'Engineering automotive software', Proceedings of the IEEE, Vol. 95 No 2, pp. 356–373.

Caniato, F., Doran, D., Sousa, R. and Boer, H. (2018), 'Designing and developing OM research. From concept to publication', International Journal of Operations and Production Management, Vol. 38 No. 9, pp. 1836–1856.

Christensen, C.M. (2006), 'The ongoing process of building a theory of disruption', Journal of Product Innovation Management, Vol. 23 No 1, pp. 39–55.

Cohen, W.M. and Levinthal, D.A. (1990), 'Absorptive capacity: a new perspective on learning and innovation', Administrative Science Quarterly, Vol. 35 No 1, pp. 128–153.

Cohn, M. (2010), Succeeding with Agile, Pearson Education, Boston.

Cooper, R.G. (2016), 'Agile-stage-gate hybrids: the next stage for product development', Research Technology Management, Vol. 59 No. 1, pp. 21–29.

Cordeiro, L., Barreto, R. and Oliveira, M. (2008), 'Towards a semiformal development methodology for embedded systems', in Gonzalez-Pérez, C and Jablonski, C. (Eds.), Proceedings of the Third International Conference on Evaluation of Novel Approaches to Software Engineering, Funchal, Portugal, 4–7 May, pp. 5–12.

Cordeiro, L., Barreto, R., Barcelos, R., Oliveira, M., Lucena, V. and Maciel, P. (2007), 'Agile development methodology for embedded systems: a platform-based design approach' in Leaney, J., Rozenblit, J.W. and Peng, J. (Eds.), Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems, Institute of Electrical and Electronics Engineers Inc., Tucson, AZ, USA, 26–29 March, pp. 195–202.

Dagnino, A. (2001), 'Coordination of hardware manufacturing and software development lifecycles for integrated systems development', Proceedings of the 2001 IEEE International Conference on Systems, Man, and Cybernetics: E-Systems and E-Man for Cybernetics in Cyberspace, Tucson, USA, 7–10 October, pp. 1850–1855.

Dawid, H., Decker, R., Hermann, T., Jahnke, H., Klat, W., König, R. and Stummer, C. (2017), 'Management science in the era of smart consumer products: challenges and research perspectives', Central European Journal of Operations Research, Vol. 25 No. 1, pp. 203–230.

Diegel, O., Singamneni, S. and Withell, A. (2008), 'A mechatronics approach to rapid product development: a case study', Proceedings of the 15th International Conference on Mechatronics and Machine Vision in Practice, Massey University, Auckland, New Zealand, 2–4 December, pp. 565–570.

Durrett, J.R., Burnell, L.J. and Priest, J.W. (2002), 'A hybrid analysis and architectural design method for development of smart home components', IEEE Wireless Communications, Vol. 9 No. 6, pp. 85–91.

Eklund, U. and Berger, C. (2017), 'Scaling agile development in mechatronic organizations. A comparative case study', Proceedings of the 39th IEEE/ACM International Conference on Software Engineering: Software Engineering in Practice Track, Buenos Aires, Argentina, 20–28 May, pp. 173–182.

Eklund, U. and Bosch, J. (2012a), 'Applying agile development in mass-produced embedded systems' in Wohlin, C. (Ed.), Proceedings of the 13th International Conference on Agile Software Development, Malmö, Sweden, 21–25 May, pp. 31–46.

Eklund, U. and Bosch, J. (2012b), 'Introducing software ecosystems for mass-produced embedded systems', in Cusumano, M.A., Iyer, B. and Venkatraman, N. (Eds.), Proceedings of the 3rd International Conference, ICSOB 2012, Springer International Publishing, Cambridge, MA, USA, 18–20 June, pp. 248–254.

Eklund, U., Olsson, H.H. and Strom, N.J. (2014), 'Industrial challenges of scaling agile in mass-produced embedded systems', in Dingsoyr, T. and Moe, N.B., Tonelli, R., Counsell, S., Gencel, C. and Petersen, K. (Eds.), Proceedings of the 15th International Conference on Agile Software Development, Springer International Publishing, Rome, Italy, 26–30 May, pp. 30–42.

Evans, R. (2009), 'Make functionality, not hardware', Military and Aerospace Electronics, Vol. 20 No. 9, pp. 16–17.

Fornaciari, W. and Sciuto, D. (1999), 'Hw/Sw codesign of embedded systems', in Harbour, M.G. and De La Puente, J.A. (Eds.), Proceedings of the 1999 Ada-Europe International Conference on Reliable Software Technologies, Santander, Spain, 7–11 June, pp. 344–355.

Greene, B. (2004), 'Agile methods applied to embedded firmware development', Proceedings of the Agile Development Conference, Salt Lake City, USA, 22–26 June, pp. 71–77.

Haghighatkhah, A., Banijamali, A., Pakanen, O., Oivo, M. and Kuvaja, P. (2017), 'Automotive software engineering: A systematic mapping study', Journal of Systems and Software, Vol. 128 No. 6, pp. 25–55.

Hansen, M.T. and Birkinshaw, J. (2007), 'The innovation value chain', Harvard Business Review, Vol. 85 No. 6, pp. 121–130.

Henfridsson, O., Mathiassen, L. and Svahn, F. (2014), 'Managing technological change in the digital age: The role of architectural frames', Journal of Information Technology, Vol. 29 No. 1, pp. 27–43.

Henfridsson, O., Nandhakumar, J., Scarbrough, H. and Panourgias, N. (2018), 'Recombination in the open-ended value landscape of digital innovation', Information and Organization, Vol. 28 No. 2, pp. 89–100.

Holmström, J. (2018), 'Recombination in digital innovation: challenges, opportunities, and the importance of a theoretical framework', Information and Organization, Vol. 28 No. 2, pp. 107–110.

Huang, P.M., Knuth, A.A., Krueger, R.O. and Garrison-Darrin, M.A. (2012a), 'Agile hardware and software systems engineering for critical military space applications', The International Society for Optical Engineering 2012. Sensors and Systems for Space Applications V, Baltimore, USA, pp. 1–9.

Huang, P.M., Darrin, A.G. and Knuth, A.A. (2012b), 'Agile hardware and software system engineering for innovation', Proceedings of the 2012 IEEE Aerospace Conference, Big Sky, USA, 3–10 March, pp. 1–10.

Itoh, M. (2005), 'System architecture and innovation – software and hardware integration in car navigation systems', Proceedings of the 2005 IEEE International Engineering Management Conference, St Johns, Canada, 11–13 September, pp. 616–620.

Joglekar, N.R. and Rosenthal, S.R. (2003), 'Coordination of design supply chains for bundling physical and software products', Journal of Product Innovation Management, Vol. 20 No. 5, pp. 374–390.

Karlsson, C. and Lovén, E. (2005), 'Managing new technology integration: integrating software in manufactured products', International Journal of Innovation Management, Vol. 9 No. 3, pp. 343–370.

Karlström, D. and Runeson, P. (2006), 'Integrating agile software development into stage-gate managed product development', Empirical Software Engineering, Vol. 11 No. 2, pp. 203–225.

Katumba, B. and Knauss, E. (2014), ‘Agile development in automotive software development: Challenges and opportunities’ in Jedlitschka, A., Kuvaja, P., Kuhrmann, M., Mannisto, T., Munch, J. and Raatikainen M. (Eds.); Product-Focused Software Process Improvement. Lecture Notes in Computer Science, pp. 33–47, University of Gothenburg, Gothenburg, Sweden.

Kettunen, P. (2003), ‘Managing embedded software project team knowledge’, Proceedings of PROFES 2006, Nokia Group, Finland, Vol. 150 No. 6, pp. 359–366.

Könnölä, K., Suomi, S., Mäkilä, T., Jokela, T., Rantala, V. and Lehtonen, T. (2016), ‘Agile methods in embedded system development: Multiple-case study of three industrial cases’, Journal of Systems and Software, August, Vol. 118, pp. 134–150.

Kubie, E.C. (1994), ‘Recollections of the first software company’, IEEE Annals of the History of Computing, Vol. 16, No. 2, pp. 65–71.

Kuwashima, K. and Fujimoto, T. (2013), ‘Performance measurement in product development research: a literature review’, Annals of Business Administrative Science, Vol. 12 No. 4, pp. 213–223.

Lee, J. and Berente, N. (2012), ‘Digital innovation and the division of innovative labor: digital controls in the automotive industry’, Organization Science, Vol. 23 No. 5, pp. 1428–1447.

Lerch, C. and Gotsch, M. (2015), ‘Digitalized product-service systems in manufacturing firms. A case study analysis’, Research-Technology Management, Vol. 58 No 5, pp. 45–52.

Letichevsky, A.A., Letychevskyi, O.O., Skobelev, V.G. and Volkov, V.A. (2017), ‘Cyber-physical systems’, Cybernetics and Systems Analysis, Vol. 53 No. 6, pp. 821–834.

Lwakatare, L.E., Karvonen, T., Sauvola, T., Kuvaja, P., Olsson, H.H., Bosch, J. and Oivo, M. (2016), ‘Towards DevOps in the embedded systems domain: why is it so hard?’ in Sprague, R.H. and Bui, T.X. (Eds.) Proceedings of the 49th Annual Hawaii International Conference on System Sciences, Oulu, Finland, pp. 5437–5446.

Maleki, E., Belkadi, F. and Bernard, A. (2017), ‘Systems engineering as a foundation for PSS development project: Motivations and perspectives’ in McAloone, T.C., Tseng, M.M., Mortensen, N.H., Shimomura, Y. and Pigosso, D.C.A. (Eds.); Proceedings of the 50th CIRP Conference on Manufacturing Systems 2017, Nantes, France, pp. 205–210.

Martini, A., Pareto, L. and Bosch, J. (2016), 'A multiple case study on the inter-group interaction speed in large, embedded software companies employing agile', Journal of Software-Evolution and Process, Vol. 28 No. 1, pp. 4–26.

Mocker, M. and Fonstad, N.O. (2018), 'Driving digitization at Audi', Proceedings of ICIS 2017: Transforming Society with Digital Innovation, Association for Information Systems, pp. 1–15.

Nambisan, S., Lyytinen, K., Majchrzak, A. and Song, M. (2017), 'Digital innovation management: Reinventing innovation management research in a digital world', MIS Quarterly, Vol. 41 No. 1, pp. 223–238.

Nylén, D. and Holmström, J. (2015), 'Digital innovation strategy: a framework for diagnosing and improving digital product and service innovation', Business Horizons, Vol. 58 No. 1, pp. 57–67.

Porter, M.E. and Heppelmann, J.E. (2014), 'How smart, connected products are transforming competition', Harvard Business Review, Vol. 92 No. 11, pp. 65–88.

Porter, M.E. and Heppelmann, J.E. (2015), 'How smart, connected products are transforming companies', Harvard Business Review, Vol. 93 No. 10, pp. 96–114.

Rauscher, T.G. and Smith, P.G. (1995), 'From experience time-driven development of software in manufactured goods', The Journal of Product Innovation Management, Vol. 12 No. 3, pp. 186–199.

Rottier, P.A. and Rodrigues, V. (2008), 'Agile development in a medical device company', in Melnik, M., Kruchten, G. and Poppendieck, P. (Eds.), Proceedings of the Agile 2008 Conference, Toronto, Canada, pp. 218–223.

Rottman, J.W. (2006), 'Successfully outsourcing embedded software development', Computer, Vol. 39 No. 1, pp. 55–61.

Schwaber, K. and Beedle, M. (2001), Agile Software Development with Scrum, Pearson Education, Upper Saddle River, USA.

Sommer, A.F, Hedegaard, C., Dukovska-Popovska, I. and Steger-Jensen, K. (2015), 'Improved product development performance through agile/stage-gate hybrids', Research Technology Management, Vol. 58 No. 1, pp. 34–44.

Svahn, F. (2012), Digital Product Innovation: Building Generative Capability through Architectural Frames, PhD thesis, Umeå Universitet, Umeå, Sweden.

Svahn, F. and Henfridsson, O. (2012), 'The dual regimes of digital innovation management', Proceedings of the Annual Hawaii International Conference on System Sciences, Maui, USA, pp. 3347–3356.

Svahn, F., Henfridsson, O. and Yoo, Y. (2009), 'A threesome dance of agency: mangling the socio-materiality of technological regimes in digital innovation', Proceedings of ICIS 2009 – Thirtieth International Conference on Information Systems, Phoenix, AZ, pp. 1–16.

Svahn, F., Lindgren, R. and Mathiassen, L. (2015), 'Applying options thinking to shape generativity in digital innovation: an action research into connected cars', Proceedings of the Annual Hawaii International Conference on System Sciences. IEEE Computer Society, pp. 4141–4150.

Svahn, F., Mathiassen, L. and Lindgren, R. (2017), 'Embracing digital innovation in incumbent firms: how Volvo Cars managed competing concerns', MIS Quarterly: Management Information Systems, Vol. 41, No. 1, pp. 239–253.

Svahn, F., Mathiassen, L., Lindgren, R. and Kane, G.C. (2017) 'Mastering the digital innovation challenge', MIT Sloan Management Review, Vol. 58 No. 3, pp. 14–16.

Whetten, D.A. (1989) 'What constitutes a theoretical contribution?', Academy of Management Review, Vol. 14 No. 4, pp. 490–495.

Wolfenstetter, T., Böhm, M., Krcmar, H. and Bründl, S. (2016), 'Why product service systems development is special', in Framinan, J.M., Gonzalez, P. and Artiba, A. (Eds.), Proceedings of the International Conference on Industrial Engineering and Systems Management, IEEE IESM 2015, Institute of Electrical and Electronics Engineers Inc., Seville, Spain, 21–23 October, pp. 1221–1228.

Woodward, M.V. and Mosterman, P.J. (2007), 'Challenges for embedded software development', Proceedings of the 50th Midwest Symposium on Circuits and Systems, Montreal, Canada, Vol. 1–3, pp. 524–527.

Yoo, Y. (2010), 'Computing in everyday life: a call for research on experiential computing', MIS Quarterly, Vol. 34 No. 2, pp. 213–231.

Yoo, Y., Boland, R.J., Lyytinen, K. and Majchrzak, A. (2012), 'Organizing for innovation in the digitized world', Organization Science, Vol. 23 No. 5, pp. 1398–1408.

Yoo, Y., Henfridsson, O. and Lyytinen, K. (2010), 'The new organizing logic of digital innovation: an agenda for information systems research', Information Systems Research, Vol. 21 No. 4, pp. 724–735.

Yuan, X., Liu, Y., Kang, L., Sun, Y. and Chen, Y. (2008), 'Adopting CMM in embedded software design and development', Proceedings of the International Conference on Embedded Software and Systems Symposia, Chengdu, China, pp. 50–54.

Notes

[1] In organisation theory, several terms are used to denote practices or mechanisms used to adapt process, functions, or departments to each other, including alignment, coordination and integration (see e.g., Boer et al., 2006). We use the term coordination in this paper to cover the whole range.

APPENDIX A. **HENDLER AND BOER** (2019)

Appendix B. Hendler (2019)

Hendler, S. (2019), 'Digital-physical product development: A qualitative analysis', European Journal of Innovation Management, Vol. 22 No. 2, pp. 315-334, https://doi.org/10.1108/EJIM-01-2018-0026

Digital-physical product development: A qualitative analysis

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Abstract

Purpose – The purpose of this paper is to investigate how digital and physical product development can be successfully coordinated and which new product development and contextual practices are suitable for the combined digital-physical product development process.

Design/methodology/approach – The paper is based on a multiple-case study within one company with three digital-physical product development projects as the units of analysis. The data collection and analysis are guided by an existing research model. The case study is used deductively to illustrate the model.

Findings – When combining digital and physical development processes, one or both need to change. This may lead to sub-optimization of one or both of the processes but optimizes the combined digital-physical process. Various development and coordination practices as well as contextual measures must be put into place to improve fit to the digital-physical process characteristics and mixed materiality.

Research limitations/implications – The paper illustrates the research model with case evidence and suggests tentative theory in the form of propositions. Further research needs to explore the impact of the practices and contextual measures proposed.

Practical implications – This research proposes a range of conditions facilitating the successful development of digital-physical products.

Originality/value – This paper is among the first to empirically explore the complex process of digital-physical product development. Taking a process perspective and focusing on organizational and managerial practices and the influence of context, organization theory is used as the theoretical lens.

Keywords New product development, Agile, Digital innovation, Digital-physical, Digitized products, Smart products

Paper type Research paper

1 Introduction

In today's fierce technology-driven competition with Internet of Things and Services, Servitization and Smart Manufacturing/Industry 4.0, companies are increasingly engaging with digital-physical product development by adding digital technology to previous non-digital products (Yoo et al., 2010; Porter and Heppelmann, 2015; Ardito et al., 2018). Digital-physical product development is the process of transforming ideas into commercial products, which include both a software and a tangible component (Hendler and Boer, 2019). A concrete example is the world's first smart shoe from Digitsole®, which automatically tightens, warms up or cools down your feet and connects to a mobile application with sensor information on, e.g., distance travelled and temperature.

Digital-physical product development combines traditional product development practices with software development practices, which are significantly different from each other (e.g. Broy, 2005; Woodward and Mosterman, 2007; Svahn and Henfridsson, 2012; Porter and Heppelmann, 2015; Lwakatare et al., 2016). Software development is optimized to adapt to high degrees of uncertainty in product requirements and solution methods via agile development methods. These agile methods enable fast and frequent feedback on the developing product and the ability to adapt accordingly in multiple, short, iterative development cycles of typically two weeks (Cohn, 2010). Once sufficient customer value has been developed, the software is released and subsequently improved (Cohn, 2010). Due to digital immateriality, i.e. no manipulation of tangible materials is needed, fixed costs are limited, there is no cost associated with the number of units produced, no manufacturing, no transportation time and no need to focus on the reuse of physical assets or scarce resources such as manufacturing equipment and shelf space. Thus, immateriality enables reduced cycle cost and time due to re-programmability (Yoo et al., 2010). Immaterial outputs enable late binding of many design-decisions as no manipulation of tangible materials is needed (Yoo et al., 2010) and can be delivered in small increments, which reduces the risk of product market failure.

Physical product development, in contrast, is optimized for stable exploitation of investments. It assumes high predictability of process outcomes and market demands. The typical high cost of physical manufacturing processes requires that existing assets are reused. Practices supporting that include the use of product platforms and incremental product development (Svahn and Henfridsson, 2012). Lead times are long with extensive up-front preparation and specifications are locked early (early binding) to reduce uncertainty (Svahn and Henfridsson, 2012). The development process typically involves a plan-driven approach with clear phases, such as a stage-gate process (Cooper, 1990).

The differences between the digital and physical development processes raise questions such as: how to effectively coordinate the need for early specification with the need to keep options open until late in the process, and how to effectively coordinate a focus on efficient reuse with a focus on learning? Another set of challenges concerns the context supporting digital-physical product development. There are significant differences between manufacturing and software companies, such as organization design and HR policies (Porter and Heppelmann, 2015). Can these contextual characteristics be combined effectively to support an integrated hardware-software development process?

Based on a systematic literature review of digital-physical product development, Hendler and Boer (2019) conclude that little is known about the possibilities to combine the two processes effectively. Based on their proposed research model (Figure 1), the objective of the present paper is:

To identify effective development, coordination and contextual practices supporting the combined digital-physical development process.

Although digital-physical product development is not a new phenomenon in practice, it is an immature field of research within new product development theory, with significant industrial relevance. This field is by some referred to as digital innovation (e.g. Yoo et al., 2012; Nambisan et al., 2017; Holmström, 2018). Its immaturity calls for theory building (Nambisan et al., 2017; Holmström, 2018) through descriptive research aimed at developing statements of associations in the form of models (Christensen, 2006) and the propositions or hypotheses embedded in these models. There is ample theory in adjacent fields, including physical, digital and service development and innovation theory, which is used to inspire the present research. As the research focuses on organizational and managerial practices from a process perspective and the influence of context, organization theory is used as a lens through which the phenomenon is studied. In-depth case study evidence is used to provide empirical support for the research model (Figure 1) in the form of a range of propositions. Furthermore, practical implications are inferred, which inform innovation managers of key areas that require attention when combining digital and physical product development.

Section 2 summarizes the theoretical background and the research model. Section 3 presents the case study method. Section 4 presents the results and develops propositions. Section 5 discusses the results. Section 6 concludes the paper with a summary of its contribution, a discussion of the limitations and implications for further research.

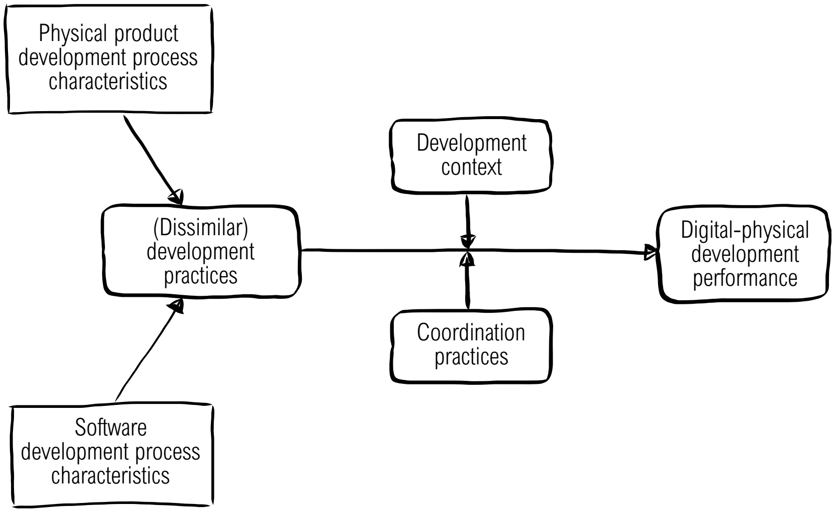

Figure 1 Research model of digital-physical product development

2 Theoretical background

According to a literature review by Hendler and Boer (2019), theory on digital-physical product development is emerging, scattered, descriptive and rarely considers the full complexity of the phenomenon. The literatures on software and physical product development have been developed relatively independently (Karlsson and Lovén, 2005; Svahn and Henfridsson, 2012). Literature on embedded software development focusses primarily on technical aspects (Haghighatkhah et al., 2017). Research on topics that may include digital-physical product development, such as complex product, product-service system, mechatronics and cyber-physical system development does uncover relevant themes such as design for product evolvement after launch, multi-disciplinarity, systems engineering and life-cycle costs (e.g. Baines et al., 2007; Wolfenstetter et al., 2016; Bialasiewicz, 2017; Maleki et al., 2017). However, theory on how to organize and manage the process is underdeveloped. The specific gaps relating to the objective guiding this research are explicated below.

2.1 Differences between digital and physical development

The literature indicates that the digital-physical product development process involves two separate development subprocesses with different development methods (e.g. Broy, 2005; Woodward and Mosterman, 2007; Svahn and Henfridsson, 2012; Porter and Heppelmann, 2015; Lwakatare et al., 2016). According to Boer and During (2001, p. 86), "[t]*he success of an innovation depends on the extent to which the "innovation manager" is able to fit the organization of the process to the demands created by* [its] *characteristics*". Uncertainty refers to the extent to which people are informed about the future (Boer and During, 2001) and may concern goals, methods, people and the influence from an organization's context (Boer, 1991). Diversity refers to the variety of the work that needs to be done in terms of the number of competences needed to perform the innovation process. Interdependence is defined as the extent to which (groups of) people depend on one another for their output (Boer and During, 2001). Complexity refers to the difficulty with which the work can be understood and has also been referred to as, e.g., comprehensibility and analysability (Boer and During, 2001).

Hendler and Boer (2019) find that digital and physical product development have different characteristics and are supported by significantly different practices. The software development process needs to make binding decisions late to exploit emergent options and utilizes agile methods that facilitate effective learning. The physical product development process needs to make binding decisions early, resulting in early maturation of the concept and specifications while often guided by a linear, staged and gated process with high cost of change later in the process. Finally, the two processes use different vocabularies and management techniques, such as detailed end-to-end project planning (physical) vs prioritized product backlogs (digital).

2.2 Alignment and coordination

Part of the literature concerning digital-physical product development focuses on the differences between the two subprocesses and observes challenges when combining them that may result in performance detriments (Hendler and Boer, 2019). Some describe examples or suggestions of how to coordinate the two processes, i.e. using various coordination mechanisms from organization theory such as integration milestones or implementing fully cross-functional teams (Könnölä et al., 2016; Eklund and Berger, 2017), however, without fully exploring their effects. Others provide examples or suggestions of how digital and physical product development practices are or could be changed and compromised to reduce the differences between them to create successful coordination (e.g. Joglekar and Rosenthal, 2003; Evans, 2009; Eklund and Bosch, 2012). Again, the performance effects are not well explored. To reduce combination challenges digital development can adapt to physical, physical can adapt to digital or both can adapt to each other (Hendler and Boer, 2019).

2.2.1 Adapting digital to physical development

Some authors observe that the long-term, plan-driven, staged and gated approach typically used in physical product development is used as the primary coordination mechanism combining all the needed development activities (Cordeiro et al., 2007; Eklund and Bosch, 2012; Lwakatare et al., 2016). This requires software development to adhere to an early and extensive planning phase with early binding, prepare the required stage-gate related documentation and adapt to governance structures and role descriptions (Joglekar and Rosenthal, 2003; Karlström and Runeson, 2006; Eklund et al., 2014). Adapting software development to the physical development methods may, however, result in reduced product performance due to software development becoming slower (Eklund and Berger, 2017) and less learning and adaptability focused (Diegel et al., 2008; Evans, 2009; Eklund and Bosch, 2012).

Other authors suggest software development to start up after the mechanical concept has been locked. This reduces the risk of the software becoming “old” before release (Eklund and Bosch, 2012) but limits the ability to optimize and co-create the full product concept (Diegel et al., 2008; Evans, 2009; Eklund et al., 2014).

2.2.2 Adapting physical to digital development

Instead of reducing the differences between the two development processes by adapting software development to a typical staged and gated process, several authors propose making the physical product development process more agile. This would allow more effective coordination and enable the physical product to be adapted to new information more easily (Huang et al., 2012). It could also enable a process in which software design decisions drive physical product design decisions, which supports the notion that the competitive advantage of digital-physical products increasingly comes from software (Evans, 2009). While some authors report successful use of agile development methods for both digital and physical product development (e.g. Huang et al., 2012; Cooper, 2016), other authors report challenges such as team composition (Eklund and Berger, 2017), management of non-interchangeable competences and a need for different coordination frequencies due to different development cycle lengths (Könnölä et al., 2016).

Other practices suggested for aligning physical product development practices with digital development involve accepting a gradual growth of requirements (Karlström and Runeson, 2006), accepting incomplete components for the digital-physical prototypes (Eklund and Berger, 2017), and using platform components to help speed up physical development cycles (Eklund and Berger, 2017).

2.2.3 Alignment and coordination practices are not well understood

Most of the literature reports examples of the digital-physical product development involving two separate development processes, with different characteristics and development practices, and with the digital process adapting to the physical process. Other sources propose that the physical process is adapted to the digital process. Some authors focus on aligning development practices (e.g. agility), others on organizing (teams) or managing (e.g. platforms) the digital-physical process, yet others on coordination of the two subprocesses. However, how to effectively coordinate the largely dissimilar and sometimes conflicting practices of digital and physical product development processes is not yet well understood in literature (Hendler and Boer, 2019).

2.3 New practices and contextual changes that fit the digital-physical process characteristics

Another part of the literature focuses on introducing new development practices or capabilities and creating a development context that suits the new digital-physical development process.

2.3.1 Suitable development practices

Development practices that could be suitable for the characteristics of digital-physical product development include horizontal and combinatorial innovation (Yoo et al., 2012), distributed innovation (Yoo et al., 2010), system interoperability (Porter and Heppelmann, 2015), rethinking existing product architectures (Yoo et al., 2010; Lee and Berente, 2012), designing for continued product enhancement after launch (Broy, 2005; Porter and Heppelmann, 2015; Eklund and Berger, 2017) and designing for security and big data (Porter and Heppelmann, 2015). However, little systematic research has been reported aimed at understanding, explaining and developing practical theory on, the specific practices needed to effectively accommodate the process characteristics of digital-physical product development.

2.3.2 The wider development context

More operational knowledge is needed on how companies can effectively accommodate digital-physical product development with a suitable context. Porter and Heppelmann (2015) suggest that manufacturing industries should learn from characteristics and practices from the software industry, such as culture, structure, strategy, HR policies and business processes outside the product development process.

2.4 Research model

Hendler and Boer (2019) propose a research model, reflecting the notions presented above. Figure 1 depicts the part of the model that is relevant for the purposes of this paper. The model includes four key constructs:

1. Development practices, which are (partly) dissimilar due to the different characteristics (uncertainty, interdependence, diversity and complexity) of the digital and the physical subprocesses. Aligning these practices, i.e. adapting them to each other, may affect development performance directly.
2. Coordination practices, which are considered to moderate the relationship between the digital-physical development process and its performance.
3. The context in which the digital-physical development process takes place may also moderate the relationship between the development process and its performance.

4. Development performance, measured in process criteria such as process cost and lead-time, and product criteria such as product quality, cost and performance (e.g. Kuwashima and Fujimoto, 2013).

Using this research model as an analytical framework, this paper aims to reduce the identified gaps in literature by elaborating on the constructs and relationships proposed by the model.

3 Method

The present research is based on a multiple-case study design with three digital-physical product development projects as the units of analysis. This method enables exploring and retaining the holistic and meaningful characteristics of a complex and contemporary social phenomenon embedded in its context (Yin, 2009). While providing empirical evidence for investigating the research objective, the case study is used deductively to illustrate the research model (Figure 1) by giving concrete examples and illustrating the nature and scope of the conceptual relationships. This is a less common but valid use of case studies for conceptual theory building (e.g. Wacker, 1998; Siggelkow, 2007; see Caniato et al., 2018).

The case company (hereafter labelled COMP) is a highly successful global company, which develops, manufactures and markets consumer products for educational purposes and entertainment. A leading company in its markets, the company was selected as it is involved in several digital-physical product development projects to which the researcher has daily access including internal communication and documents. Its elaborate and mature core product development process includes more than 100 milestones across a front-end and an execution phase. The process is orchestrated by a project team supported by a large number of functional departments working on many concurrent projects, to deliver high levels of product quality, without delays, produced in a stable and lean manufacturing system.

Exploiting the opportunity to collect robust evidence for analytical generalization, all three digital-physical product development projects active at the time of data collection, hereafter named Project A, B and C, were selected for study. These projects were the first to deliver on the company strategy of digitally augmenting its manufactured products. All projects involved extensive collaboration with world-class external software partners using state-of-the-art technology and agile development practices. The resulting products include physical and software components, which are integrated in use by the user via a third-party device, for example a mobile phone using combination technology such as visual recognition. Project A had one product launch cycle, while projects B and C launched products over several years.

Data were collected from November 2014 to November 2017 through 50 interviews with key functional areas from each project, two hours of workshop observation, 19 documents, notes from informal conversations and 110 h of participation in process design-related project tasks, which all enabled triangulation. Table I presents a detailed overview of the collected data per project.

Table I Overview of the collected data

Project A	Project B	Project C
Role of interviewee in project (number of interviews) (duration of each interview):		
Product designer A (1) (1h) Product designer B (1) (1h) Digital project manager A (2) (1h) Project manager B (1) (1h) Marketing A (2) (1,5h + 0,5h) Marketing B (1) (1h) Internal digital producer A (2) (1h) Internal digital producer B (1) (1,5h) Line manager A (1) (1h) Line manager B (1) (1h) Consumer insights (1) (1h) External digital producer (1) (2h)	Technical project manager A (2) (1h) Technical project manager B (1) (1h) Line manager (1) (1h) Marketing (2) (1+1,5h) Project management (1) (1h) Digital marketing (1) (1h) Digital producer (2) (1+0,5h) Designer A (1) (1h) Designer B (1) (1h) External digital producer A (1) (2h) External digital producer B (1) (0,5h)	Digital project manager A (1) (1,5h) Digital project manager B (1) (1h) Digital project manager C (2) (1h) Project manager A (1) (1h) Project manager B (1) (0,5h) Project manager C (1) (2h) Digital line manager (2) (1h) Digital designer A (2) (1h) Digital designer B (1) (1h) Digital producer A (1) (1h) Digital producer B (2) (1h) Digital producer C (1) (1h) Designer A (1) (1h) Designer B (1) (1h) Designer C (1) (1h) Marketing (1) (1h) External digital producer (1) (1h)

Other collected data:		
• Archival data (escalation report, ‘lessons learned’ report for full project, ‘lessons learned’ report for collaboration between COMP and the digital partner, project plan) • Approx. 10 informal conversations with project management and digital project members • Notes from facilitating an end-to-end process design for digital-physical product development with project management (approx. 100 hours)	• Archival data (process suggestions from a project designer, project observations from a technical project manager, ‘lessons learned’ report for partnership capability building, project organization and role chart, project schedule) • Approx. 5 informal conversations with digital project participants	• Archival data (‘lessons learned’ report for full project, ‘lessons learned’ report for marketing, project organization charts, concept diagrams, project plan) • Observation of a 2 hour ‘lessons learned’ workshop • Approx. 10 informal conversations with project management and digital project members • Notes from participating in the design of a parts of a digital-physical front-end process early in the project together with project management (10 hour)

Most interviews were carried out during the unfolding projects and were semi-structured with open-ended questions to allow for exploration of emerging topics and hypothesizing about cause-effect relationships. Each interview lasted one hour on average and started with a collection of background information including the interviewee’s project role and work experience. Ten of the interviewees were interviewed twice to follow-up on key topics. The interviews were guided by the questions:

1. Which challenges/opportunities have you experienced when combining the digital and the physical development processes?
2. What were the actual mechanisms encountered?
3. How did you cope with challenges/exploit opportunities, if you did?
4. What key knowledge was gained for next time?

Before the end of each interview, the key summary statements were presented back to the interviewee to correct for misunderstandings. The interviews were recorded and transcribed. As illustrated in Figure 2, the collected data were condensed and ordered into a database of statements from which data were extracted and summarized into two tables per project, one focusing on the dissimilarities between digital and physical development and the alignment and coordination practices needed to overcome these differences, the other on new practices including the contextual changes needed to accommodate the new characteristics and materiality of the combined digital-physical product development process. Next, the data were analyzed through the lens of the research model by grouping paper slip representations of the table rows, first within and, then, across the individual projects. Finally, the paper slips were grouped to extract propositions. To avoid misinterpretation, continuing informal conversations with project members allowed quick feedback during the data analysis.

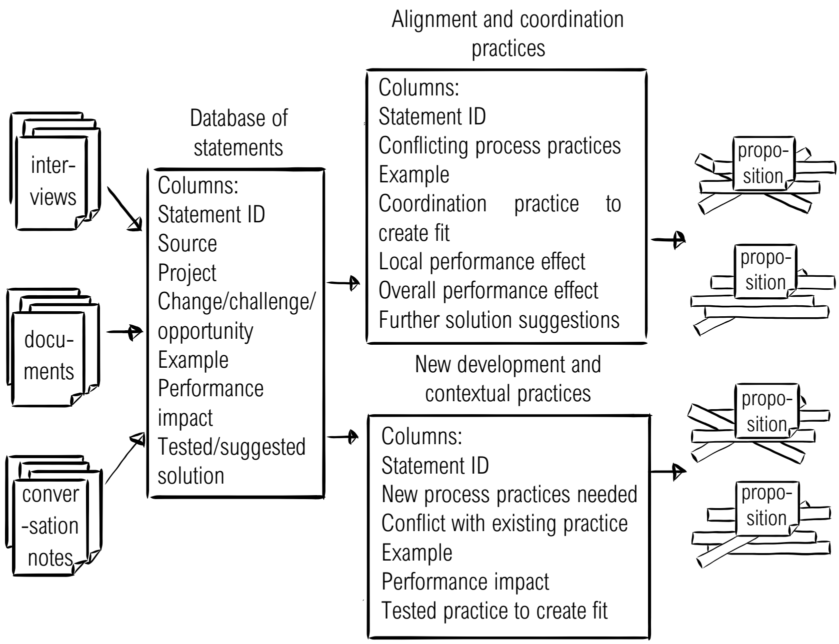

Figure 2 Analytical coding process

4 Results

4.1 The digital and physical product development process characteristics

The research is based on the fundamental assumption that digital and physical development have different characteristics. The aim of this subsection is to verify this assumption.

Projects A, B and C all involved a collaboration with digital partners with largely similar agile development methods. Relative to COMP's physical product development process, their digital product development processes are adapted to a higher degree of uncertainty, a lower degree of diversity and similarly high degrees of interdependence and complexity. The high degree of uncertainty stems from a rapidly evolving digital technology, industry structure, competitor landscape and consumer preferences. One of the digital partners explained: "*Our R&D team continuously looks into improving our technology, which needs to be leading edge to be competitive. If we were to lock months before release* [like COMP does], *we would be [several] months behind".* The diversity is considerably lower for digital development with 3–4 competence areas represented in the digital cross-functional teams, whereas approx. 50 distinct competences are involved in the physical product concept design.

The digital and physical development practices can to a large extent be explained by these process characteristics and materiality. For the digital partners, digital immateriality enables short and low-cost development cycles, several releases per product and late binding which, coupled with high degrees of complexity and uncertainty, goes a long way to explain the iterative and emergent agile development process with short up-front planning and the possibility to quickly adapt to new information via empowered decision-making, cross-functional teams, a floating scope (product requirements) and highly formalized two-week sprints. The lower degree of diversity enables the use of smaller cross-functional teams, easier mutual adjustment and the use of one or a few product vision holders as there is no need to re-interpret the vision across multiple knowledge domains, all of which enable fast adaptation to maximize consumer value.

In comparison to digital development, COMP's product development process is characterized by higher diversity, lower uncertainty and physical materiality, resulting in one long development cycle with a limited number of product spirals, higher cycle costs and early binding due to logistics and manufacturing. Consequently, COMP's development process is designed to launch products reliably in accordance with extensive up-front planning via a highly formalized, high-level schedule-bound plan with hierarchical decision making, which leaves little room for exploration and adaptation in the latter part of the process. Unforeseen changes are primarily managed by adjusting project staffing and/or workload. The focus on consumer value is balanced with schedule, cost and risk considerations. High degrees of diversity and complexity result in multiple product vision holders to ensure translation across domains, consensus decision making and coupled with low market uncertainty, a largely functionally-oriented organization. The digital development requires approx. one year whereas the physical process is approx. twice as long. Thus, optimal execution of digital-physical product development requires two different ways of organizing them:

P1: Compared to physical product development, the digital development process is characterized by a higher degree of uncertainty, a lower degree of diversity and digital immateriality, which allows for an adaptability-optimized development process of short, iterative development cycles with predominantly cross-functional, teams, empowered decision-making, one product vision holder, a floating scope, short development cycles, late binding, short up-front planning and several releases per product.

P2: Compared to digital development, the physical product development process is characterized by a lower degree of uncertainty, a higher degree of diversity and a physical materiality, which allows for a stability-optimized development process of one long development cycle with a large extent of functional unit grouping, hierarchical and consensus driven decision-making, multiple product vision holders, a highly formalized and high-level, schedule-bound development process, early binding, extensive up-front planning and one launch per product.

4.2 Combining digital and physical development through alignment

This subsection aims at identifying attempts made to align the digital and physical subprocesses by adapting one to the other or both to each other.

All three projects engaged with external software companies after concept lock, which is later than the physical development teams had desired in hindsight. Reasons included a late realization of the positive impact from collaborating in the front-end, difficult contract negotiations and shorter digital development lead-time. Nevertheless, the late entry left enough time for the development of digital experiences. At the time of entry, physical development was getting ready to start handing over specifications to manufacturing and marketing material development, which meant that the digital partners had to adapt quickly to the physical development process due to many design interdependencies. Partner C explained, "*We had to adapt, and we did this time around, but with much difficulty,* […] *extra cost and lower product quality".* The physical development process also had to allow a large amount of exceptions such as schedule delays caused by the digital product immaturity.

Learning from experience, projects B and C managed to engage digital development earlier and earlier in the subsequent front-end cycles, particularly to mitigate a large amount of exceptions to the process schedule. Both projects successfully achieved their targets. Project A experienced problems with poor quality in the digital-physical interface of one of its products but otherwise met its targets, too.

The digital processes were the ones adapting the most by maturing more parts of the digital experience much earlier to be able to accommodate the early binding of interdependent design-decisions and deliverables in the first part of the development process. These interdependent decisions included the packaging graphics and the bill of materials (BoM). Locking the packaging graphics design required the digital partners to supply screenshots from the digital experience long before they were ready. Partner A explained how they had to "fake" a screenshot and feature list based on what they predicted could be a great experience for the consumer, costing extra unplanned resources at the time. One project member stated, "*The project had to stick with a less fun* [software] *experience, because we had already put it on the box preventing us from developing a more fun* [experience]". Learning from this, Project C settled on preparing thematically similar imagery without screenshots, which was sufficient to indicate the core idea of the digital experience and resulting in a relatively less reduced digital solution space. The quality of the resulting imagery was not considered to be as high as desired.

The digital partners also felt confined due to the user instructions and other marketing materials that had to be locked early, such as a video demonstrating the product use, which had to be shipped to the shops on relevant devices in good time before launch. New videos had to be made after launch to reflect the final digital experience:

P3: With high interdependency between digital and physical product development, imposing the early binding typical of physical development is limiting the subsequent exploitation of new knowledge in digital development, hence, reducing the digital adaptability and the potential value of the digital-physical product.

The many (inter)dependencies between digital and physical development took all three projects by surprise in their first launch cycle, causing significant disruptions. The software partners experienced how physical development perceived software change requests to have very low costs. Partner C explained how these many changes took away time that could have been used better. Partner A also explained how the project failed to create transparent task management, resulting in COMP not being aware of which other tasks had to be de-selected in favor of new tasks. The digital partners all compensated by adding resources and reprioritizing work. However, the first product launch of projects A and B suffered from several quality problems. The software was updated after launch. However, some problems, such as a large file size, could not be fixed easily after launch.

All projects experienced positive effects from digital mitigating physical errors. After a launch from Project B, when approx. 40,000 products had been shipped to the shops, an error was detected in an electronic component that was detrimental to the functioning of the product. Fortunately, the software partner could update the software within a few days and mitigate the physical problem. The physical marketing manager explained, "*We saved huge costs and a damaged brand by avoiding calling back the product. Fantastic!*"

In all three projects, the physical design constraints dominated the overall design decisions. Project B, for example, had to build physical products that were to be replicated digitally and enhanced with various digital functionalities. After having passed the design back and forth between digital and physical, the project team decided to have the physical designers develop two-three options per product, leaving plenty of scope for creating enough digital variety (the main digital constraint).

Running out of time for the BoM, some suboptimal physical design-decisions were made. Again, the software designers compensated for the early binding by manipulating the objects in the digital realm.

The reduced digital solution space from the early binding and the physical design constraints did not result in unacceptable product quality due to an adaptability-optimized software development process and the intangible immateriality, leaving many design options open late in the project:

P4: Digital development can adapt easier to the requirements of the physical development process as well as absorb some of its undesired variability, without causing a significant quality decrease of the product.

With P4 in mind, partner B successfully sharpened its agile processes by becoming more cross-functional to increase its ability to react to unforeseen changes from the many interdependencies between digital and physical. Physical product development also supported the digital process adaptability by giving fast feedback for the digital development sprints. According to Partner C, COMP gave faster feedback than their regular clients, i.e. within 24 h, which enabled the partner to incorporate this into the next sprint and, thus, adapt fast:

P5: Supporting and even accommodating more agility in digital development (if not already fully adaptability-optimized) helps software development to adapt to the increased uncertainty from combining with physical product development.

Digital development continuously struggled to deliver the right quality at the right time for the early milestones. Accordingly, all three projects experienced delays and changes to the BoM, which challenged multiple dependencies between product, marketing and manufacturing development. The pre-planned allocation of people's time made it difficult to re-schedule the many concurrent development projects worked upon by the largely functional organization of COMP. This caused the projects to spend a lot of time on stakeholder management, filling in forms, waiting for hierarchical decision making, while causing stress and overtime. A project manager from Project C described, "*We do need a standard [product development] process, but we need more flexibility to customize it. Today, it is very cumbersome and resource demanding to argue sufficiently to be allowed to deviate from the plans".* The delays also caused budget overruns. For example, Project C failed to deliver a digital file on time due to bugs, which incurred extra cost for an external marketing production company. The delays also increased the risk of errors, as tasks had to be "hand-carried" through otherwise standardized subprocesses. Due to the overall highly complicated development process, this brought with it the risk of neglecting standardized information flows or quality assurance processes. In other cases, the delayed digital deliveries meant that design decisions had to be made without input from the digital partner. The number of exceptions related to the changes to the budget, the schedule and the BoM far exceeded the average project and resulted in much time spent on exception management. One of the project managers admitted, "*We should have categorized this project as high risk and high complexity from the start"*.

Project B stood out, as it adapted to radically new concept ideas from their digital partner after the concept lock milestone, by successfully hacking the established development process. One project member stated, "*We forced this project into a standard process that did not fit. Once we realized this, the project started to turn for the better"*. The project learned to change and fit the plan to new circumstances, negotiate new timelines and resources with stakeholders and speed up development work via, e.g., more digital-physical co-location. According to one of the leading project team members, the team pulled off one of the biggest stunts in recent COMP history, however, with increased risks, stress, overtime and budget.

All three projects agreed that more flexibility and adaptability should be planned into the physical product development process using, for example, more schedule buffers and plan for more adaptability after launch. One project member noted, "*There are no [physical] design resources available to ensure consistency between digital and physical later in the downstream phase. They are now working on the next thing. Their resources are not available anymore"*. According to Project B it is still not clear how much the digital or the physical product development processes should be adapted to each other. Nevertheless, all projects proposed that COMP should put some effort into reducing lead times for critical path processes, i.e. accommodating later binding, to better accommodate digital-physical product development projects:

P6: In case of a high degree of interdependence, the physical product development process is bound to experience high levels of exception management and can benefit from building more flexibility into the process, including later binding and slack, to accommodate the added uncertainty from the digital development process.

So, the overall picture emerging is a combination of physical becoming more flexible and digital becoming less adaptable. Had none of the partners adapted, a successful conduct of the two processes with current technologies would have been unlikely:

P7: When combining a physical stability-optimized product development process and a digital adaptability-optimized development process, either the former must become more adaptable, the latter must become less adaptable or both need to change, which may reduce the performance of one or both subprocesses but should lead to optimal performance of the overall process.

4.3 Coordinating the digital and physical subprocesses

While the previous analysis focuses on changes that took place within the two subprocesses, other actions were taken between the two processes through a range of coordination mechanisms.

Digital development had to adapt by increasingly engaging in an extensive front-end due to many design interdependencies. Initially, the digital partners were commencing their processes after concept lock, i.e. after the front-end work, leaving little digital solution space and a short time until key milestones. Including the partners into the projects took a long time and the digital-physical product concept was lacking the partners' digital competences. Partner C explained how the digital concept created by the largely physical designers did not align with good digital practices in terms of language, graphics, colours and reuse options that would enable an efficient development process. Partner C explained, "*We did not feel we had a lot of freedom to challenge* […] *Had we been involved earlier in the process or allowed to change concepts the result would have been a better system".*

Engaging the digital partners earlier in the front-end processes was not easy due to a lack of digital front-end capabilities at the partner companies'. Partner B explained, "*Historically we have not been involved in front-end processes. It was quite difficult for us to be involved in the process, but not unenjoyable. The front-end guys are a bit mad as they are not considering constraints. When we generate ideas, we always consider the constraints so it required a new frame of mind for us".* One partner hired new people to meet the front-end needs. Another struggled to allocate resources and found that hiring front-end resources conflicted with their operating model, especially since their other clients did not have this need. Nevertheless, the digital partners increasingly engaged more in the front-end work by delivering demonstration videos and co-locating digital and physical designers for short periods of time with good effects on performance. Still, the digital partners were not allocating enough time for front-end from the perspective of the physical development teams.

Consequently, the physical development drove many of the design-decisions that should have been digital-physical interdependent. Particularly in Project B, insufficient early digital involvement in the first front-end cycle contributed to the project restarting concept development.

In contrast to COMP, the digital partners preferred not starting digital development earlier on. Partner B explained that finishing well before launch and, in effect, aligning with COMP's development schedule before handing over to production, would remove much of the motivating urgency for the software developers and make the digital solution outdated before launch, causing extensive and expensive retrofitting of the product to the newest technology, features, devices and digital platforms:

P8: If digital and physical collaborate toward early physical binding, digital development is more likely to be able to successfully adapt to the early binding and design constraint from the physical product development process.

Physical product development needed to learn about a new knowledge domain. Talking about the digital and physical language differences, a physical graphic designer from Project C explained: "*It's like speaking French and German*" when both sides tried to understand each other's design constraints. It was difficult for the physical teams to understand the digital development process and the actual cost of change. Partner B explained, "*We were asked to add and change stuff quite often, with no consideration of what it costs, what not to do instead, etc. Being immature to software development,* [COMP] *did not understand how complicated it is, especially supporting a large array of devices".* Similarly, it was hard for the digital teams to understand manufacturing constraints, such as how readily COMP was willing to compromise digital product quality to avoid the high cost of delay within the physical value chain by, e.g., missing out on a shelf space reservation in shops. A digital producer from Partner C explained: "*In digital you don't fight just as hard to reach a deadline, as you can typically release a patch later that can fix the problem".*

To reduce the knowledge gap, internal digitally knowledgeable project members taught the physical development teams about digital development methods and language. The projects utilized such employees as liaison roles, helping to translate on behalf of both sides. Unfortunately, these roles did not always understand the manufacturing processes and the cost of delay. To further reduce the knowledge gaps the projects increasingly focused on establishing digital-physical face-to-face time in the form of cross-functional teamwork and multiple joint problem-solving sessions:

P9: To avoid faulty assumptions and, thus, ineffectiveness, digital-physical product development can benefit significantly from ensuring cross-functionality, good collaboration skills, a shared language and understanding of schedule and design constraints, the cost of delay, the impact of uncertainty and the cost of change associated with that.

Despite the sub-optimization and the digital partners compromising their adaptability to a large extent, all projects were considered successful. Performance losses were largely absorbed or hidden by other performance effects, buffers, inaccurate budgeting and planning or digital development mitigating physical risks or errors after launch. This shows the importance of making the right trade-offs throughout the digital-physical product development process to carefully trade in a process sub-optimization effect for a more significant performance gain. As one project manager from Project C put it: "*If we only knew the cost of delay* [of milestones], *we could better decide how to solve our problems*". Project B, in which the physical development process was adapted the most, had several similar learning points. According to the physical team: "*We need to jointly design and plan our processes up* *front to fit* [the nature] *of the project*," "*We need to lock the specification according to project risk and not when the schedule tells us to*" and "*Forcing our way of working may be too risky".* Thus, making these trade-offs requires close cooperation and effective communication to estimate the performance effects across both domains:

P10: In order to optimize a performance gain from combining the digital and the physical product development processes, managing the trade-offs between these processes requires close collaboration and effective communication.

4.4 New practices and contextual changes

The cases also show that new practices and contextual changes were adopted and implemented to accommodate the new characteristics and materiality of the combined digital-physical product development process. Table II presents an overview and also includes practices recommended by project members that were not (sufficiently) implemented as well as the perceived performance effects of not fully adapting to the new characteristics.

4.4.1 Uncertainty

COMP's project teams did not have experience with digital product development. Combined with the relative innovativeness of the new digital-physical products, this contributed to a higher uncertainty in the product requirements and schedules. This was further aggravated in the case of Project B, which entered a new and much more volatile market segment with new competitors, consumer needs and supply methods.

Due to the increased uncertainty, the flexibility needed within COMP often exceeded the planned limits. This triggered the projects to front-load and enable more agility via, e.g., highly experienced project members, more cross-functionality and more schedule buffers (see Table 2). The project members suggested many additional changes to the ones implemented, such as requesting more flexibility in budget and resource planning, T-shaped resources and using shorter prototype development cycles.

The higher uncertainty and the digital immateriality encouraged COMP to spend more time on understanding the market, return policies and business models. The existing policies and models failed to answer key questions, e.g., regarding the digital distribution. Other new practices involved innovative ways of communicating the new digital-physical value propositions to the marketplace and ensuring that the products remained relevant to the market after launch via product monitoring, maintenance, improvements, product data collection, data analysis and decision-making to react with new marketing communication or additional budget allocations for software updates.

Another challenge for the projects was the insufficient support from a slow moving and largely physical product platform development process. Consequently, the projects had to engage with uncertain technology development themselves. Finally, the rapidly developing digital technologies required a more external orientation, not only to ensure access to state-of-the-art digital technologies and information about a fast-moving market, but also to expand the stakeholder management of the projects to include interfacing systems such as operating systems, devices and app stores.

4.4.2 Diversity

COMP's digital development resources were scarce, so several resources were hired. The digital competences caused significantly larger and more diversely staffed projects. The project management team initially doubled in size, to include the digital competences needed to manage the new digital-physical interdependencies and requirements. The projects also employed digital competences specific to marketing, software development, software development management, data analysis and

Table 2 Overview of new practices and contextual changes with performance effects of not fully adapting to the new process characteristics

Practices and context	Performance effect
Uncertainty *Implemented:* • Much ad hoc problem-solving • Increased stakeholder management and network driven execution • Highly experienced project members comfortable working with high uncertainty • Ad-hoc design of new support processes • More schedule buffers • More cross-functional co-location • Front-load work to avoid schedule delays • More front-end project members continuing to execution phase to avoid knowledge loss • Establishment of some post launch operations • More time spent on understanding new market category *Suggested:* • Stronger collaboration/co-creation across digital and physical • Stronger risk focus • Shorten physical prototype development cycles • More and dedicated technical subject-matter experts in front-end to make 'proof of technology' • More T-shaped resources • More and earlier allocated IPR competences	• Team stress/overtime • Higher process cost • Lower product quality

• Understand cost-of-delay for milestones • Faster project governance decision making • More risky business cases allowed • Fast reaction to post launch market feedback beyond digital, e.g. marketing or pricing • New return policies • More reactive planning of processes, budgets and people • Shorten long lead-time processes to enable later binding • Digital platform development • More focus on marketing innovation • Mature and anchor post lunch operations	
Diversity *Implemented:* • New digital competences • New digital technology to help develop digital prototypes *Suggested:* • Digital partner contract negotiation skills • New digital operating model competences and models • More digitally competent management	• Lower product quality • Higher process cost
Interdependence *Implemented:* • Early and stronger focus on dependencies • Cadenced coordination meetings • More coordination competences • Cross-functional problem solving • Multi-domain liaison role • Some digital-physical co-location • New project organization • Clarified roles *Suggested:* • Physical design should not be in the lead per default • Improve partner collaboration skills	• Lower product quality • Higher process cost
Complexity *Implemented:* • More problem-solving loops • The best subject matter experts	• Lower product quality

- New testing methods

Suggested:

- Policies for when to use internal or external competences
- More T-shaped resources
- Better on-line collaboration tools for non-co-located collaboration
- Define digital quality acceptance criteria

technology scouting. In addition to these competences the projects requested digital competences for areas such as business model development, purchasing (partner contract negotiations) and project governance. Lacking digital insight at governance and advisory board level made it difficult to communicate efficiently, get help to remove digital specific project impediments, and understand risks and consequences. All these competences were needed in addition to the digital partners' competences to enable successful front-end execution, project management, product development and product quality assurance and, in effect, deliver the projects successfully. The new roles were largely employed within various existing departments in COMP.

4.4.3 Interdependence

The projects experienced many digital-physical interdependencies. Relative to Project A and B, Project C experienced a lower degree of interdependencies after the concept lock in the second launch cycle, as clear interfaces between digital and physical product components had been designed in a mature product architecture, allowing replacing interdependencies from the first launch cycle with dependencies in the following cycles. Other than suggesting better online collaboration tools, the responses to the higher degree of interdependence included a new focus on dependency mapping, multiple cadenced coordination meetings, integrating activities more on a task level via some co-location in the early project phases and hiring digital coordination competences to also function as liaison roles.

4.4.4 Complexity

The perceived complexity of the digital-physical product development process increased due to the integration of digital product components, which introduced more requirements and made problems more multi-faceted. A physical product designer from Project A explained how they not only had to work with and learn about additional design requirements, requiring the best experts, but also how they spent more time on problem solving as many problems could have several causes: physical, digital or the integration between them. The projects also discovered that the mixed materiality of the integrated digital-physical prototypes required new testing criteria and methods. Furthermore, with bugs being a given to most software, all projects were challenged by a lack of digital quality guidelines. Finally, the projects invested in digital tools and devices, for example to make digital-physical prototypes in the front-end process:

P11: Compared to traditional physical product development, digital-physical development is likely to involve a higher degree of uncertainty, interdependence, complexity and diversity that, coupled with the digital materiality, requires changes in product development practices, including rethinking marketing strategies, becoming more externally oriented, developing new testing methods, organizing the project to include digital competences at all levels and focusing on product architecture and dependency mapping.

P12: Compared to traditional physical product development, digital-physical development is likely to involve a higher degree of uncertainty, interdependence, complexity and diversity that, coupled with the digital immateriality, requires changes in the development context, including business model innovation, rethinking marketing operations, establishing post launch operations and new digital quality acceptance criteria, rethinking product platform(s), investing in digital tools, and ensuring digital competences for project governance and support functions including marketing, business model development and purchasing.

5 Discussion

This research contributes to conceptual theory building within the immature field of digital-physical product development. It uses deductive reasoning by taking a starting point in a literature-based research model, exemplifying the model and developing twelve case study-based propositions on its constructs and relationships – see Figure 3.

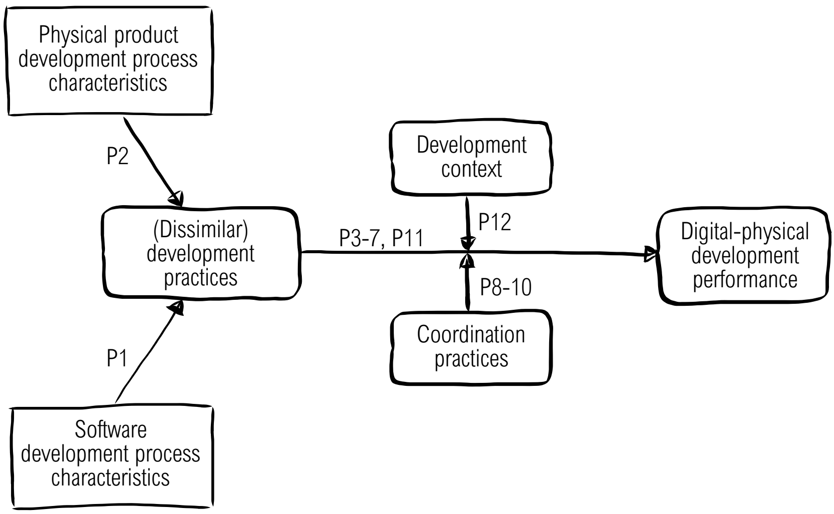

Figure 3 The research model and propositions

The case studies confirm that digital and physical development processes differ in terms of uncertainty, diversity (Boer and During, 2001) and materiality, which leads to dissimilar organizational and managerial practices supporting these processes (e.g. Broy, 2005;Woodward and Mosterman, 2007; Lwakatare et al., 2016; Porter and Heppelmann, 2015; Lwakatare et al., 2016) and explains why the two processes are executed separately (Propositions 1 and 2).

Three supplementary strategies can be used to combine digital and physical development effectively:

1. align the two subprocesses, i.e. adapt them to each other;
2. coordinate the two subprocesses; and
3. create new development practices and a suitable development context.

Adapting the digital process to the physical development process does not necessarily hamper quality (Proposition 4). However, imposing early binding, which is typical for physical development, limits the exploitation of new knowledge in the digital process, and reduces the digital adaptability and the potential value of the digital-physical product (Proposition 3). Options to mitigate these problems include adapting the physical to the digital process through a more agile development approach (e.g. Cooper, 2016) (Proposition 5), enabling the later binding typical for digital development (Yoo et al., 2010), adding more slack (Proposition 6) and adapting the two subprocesses to each other (Karlström and Runeson, 2006; Eklund and Berger, 2017; Könnölä et al., 2016) (Proposition 7). Altogether, however, it seems that it is easier for software to adapt to physical product development (e.g. Cordeiro et al., 2007; Eklund and Bosch, 2012), rather than the other way around, and adopt a long-term, plan-driven, stage-gate approach to dominate the combined process (Cordeiro et al., 2007; Eklund and Bosch, 2012; Lwakatare et al., 2016).

In any case, the two subprocesses take place separately during the majority of their execution (e.g. Evans, 2009; Huang et al., 2012; Cooper, 2016), especially if the digital subprocess is outsourced. Complete alignment may not be possible or fail to create the desired performance effects. In that case, additional mechanisms are needed, to coordinate the two subprocesses. The case studies suggest various coordination mechanisms, including early collaboration to reduce the early binding problem (Proposition 8), cross-functionality (Könnölä et al., 2016; Eklund and Berger, 2017), collaboration skills and a shared language and understanding of schedule and design constraints, the cost of delay, the impact of uncertainty and the associated cost of change (Proposition 9). In addition, new development practices are needed such as a digital-physical marketing strategy, external orientation, new testing methods, including digital competences at all levels in the project organization and a focus on product architecture and dependency mapping (Proposition 11). Finally, a context suiting the combined digital-physical development process is needed, which better reflects the typical software development environment (Porter and

Heppelmann, 2015) and also includes rethought marketing operations, post launch operations and new digital quality acceptance criteria, digital-physical product platform(s), investments in digital tools and digitally competent project governance, marketing, purchasing and business development (Proposition 12). Figure 3 positions the propositions in the research model depicted in Figure 1.

6 Conclusion

6.1 Contribution

This paper empirically explores the complex process of digital-physical product development. Taking a process perspective and focusing on organizational and managerial practices and the influence of context, organization theory is used as the theoretical lens.

The paper takes a starting point in a research model, investigates its constructs and relationships, and offers tentative explanations in the form of twelve propositions for further research of digital-physical product development. The propositions suggest that, when combining a physical stability-optimized and a digital adaptability-optimized development process, either the former must become more adaptable, the latter must become less adaptable or both must change, which in all cases reduces the performance of either or both subprocesses. A combination of actions remedies this problem and leads to optimal performance of the combined process: adapting either or both of the subprocesses to the other, effective coordination between the two subprocesses and implementation of new development practices and a suitable development context. Trade-offs are inevitable, though, and require effective coordination and communication between the stakeholders involved.

The practical implications of the research are embedded in the propositions and summarized in Table II. They align with and add to observations made in previous literature and offer valuable guidelines for manufacturing companies toward understanding important trade-off, process and context design decisions supporting digitalizing manufacturers in an increasingly fast-moving environment.

6.2 Limitations and further research

The research is based on a study of multiple projects in one large, mature and highly successful company, which allows creating detailed insight but also presents some important limitations related to method and context. Avenues for future research include exploring the topic and the proposed propositions from the perspective of a smaller or less mature manufacturer, a software company that is adding a physical product dimension, or a born digital-physical product development company. Further exploration in the form of case studies or action research is needed to understand which coordination practices or scenarios are most effective and in which contexts, while larger scale studies are needed to move from tentative theory and test the propositions.

The research took its starting point in the processes of digital and physical development and used organization theory as the lens to investigate organizational, managerial and contextual aspects. Other relevant lenses include a resource or knowledge-based perspective, which would help study the role of IT systems and the ability of manufacturers to provide and implement the right practices and context, i.e. development and managerial competences, as well as dynamic capabilities and absorptive capacity.

References

Ardito, L., D'Adda, D. and Messeni Petruzzelli, A. (2018), 'Mapping innovation dynamics in the internet of things domain: evidence from patent analysis', Technological Forecasting and Social Change, Vol. 136, p. 317-330.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M. and Wilson, H. (2007), 'State-of-the-art in product-service systems', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 221 No. 10, pp. 1543-1552.

Bialasiewicz, J.T. (2017), 'Interaction of concurrent processes in cyber-physical systems', Proceedings of the 14th International Conference on Industrial Informatics, INDIN 2016, IEEE, Poitiers, July 19-21, pp. 516-521.

Boer, H. (1991), Organising Innovative Manufacturing Systems, Gower, Aldershot.

Boer, H. and During, W.E. (2001), 'Innovation. What innovation? A comparison between product, process and organisational innovation', International Journal of Technology Management, Vol. 22 No 1-3, pp. 83-107.

Broy, M. (2005), 'Automotive software and systems engineering', Proceedings of the 3rd ACM & IEEE International Conference on Formal Methods and Models for Co-design, Verona, July 11-14, pp. 143-149.

Caniato, F., Doran, D., Sousa, R. and Boer, H. (2018), 'Designing and developing OM research – from concept to publication', International Journal of Operations & Production Management, Vol. 38 No. 9, pp. 1836-1856.

Christensen, C.M. (2006), "The ongoing process of building a theory of disruption", Journal of Product Innovation Management, Vol. 23 No. 1, pp. 39-55.

Cohn, M. (2010), Succeeding with Agile, Pearson Education, Boston, MA.

Cooper, R.G. (1990), 'Stage-gate systems: a new tool for managing new products', Business Horizons, Vol. 33 No. 3, pp. 44-54.

Cooper, R.G. (2016), 'Agile-stage-gate hybrids: the next stage for product development', Research Technology Management, Vol. 59 No. 1, pp. 21-29.

Cordeiro, L., Barreto, R., Barcelos, R., Oliveira, M., Lucena, V. and Maciel, P. (2007), 'Agile development methodology for embedded systems: a platform-based design approach', in Leaney, J., Rozenblit, J.W. and Peng, J. (Eds), Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems, Institute of Electrical and Electronics Engineers Inc, Tucson, AZ, March 26-29, pp. 195-202.

Diegel, O., Singamneni, S. and Withell, A. (2008), 'A mechatronics approach to rapid product development: a case study', Proceedings of the 15th International Conference on Mechatronics and Machine Vision in Practice (M2VIP), Massey University, Auckland, December 2-4, pp. 565-570.

Eklund, U. and Bosch, J. (2012), 'Introducing software ecosystems for mass-produced embedded systems', in Cusumano, M.A., Iyer, B. and Venkatraman, N. (Eds), Proceedings of the 3rd International Conference, ICSOB 2012, Springer International Publishing, Cambridge, MA, pp. 248-254.

Eklund, U. and Berger, C. (2017), 'Scaling agile development in mechatronic organizations: a comparative case study', Proceedings of the 39th IEEE/ACM International Conference on Software Engineering: Software Engineering in Practice Track, ICSE-SEIP 2017, Department of Computer Science and Media Technology, Malmö University, Institute of Electrical and Electronics Engineers, Malmö, pp. 173-182.

Eklund, U., Olsson, H.H. and Strom, N.J. (2014), 'Industrial challenges of scaling agile in mass-produced embedded systems', in Dingsoyr, T., Moe, N.B., Tonelli, R., Counsell, S., Gencel, C. and Petersen, K. (Eds), Proceedings of the 15th International Conference on Agile Software Development, Springer International Publishing, Rome, May 26-30, pp. 30-42.

Evans, R. (2009), 'Make functionality, not hardware', Military & Aerospace Electronics, Vol. 20 No. 9, pp. 16-17.

Haghighatkhah, A., Banijamali, A., Pakanen, O., Oivo, M. and Kuvaja, P. (2017), 'Automotive software engineering: a systematic mapping study', Journal of Systems and Software, Vol. 128, June, pp. 25-55.

Hendler, S. and Boer, H. (2019), ”Digital-physical product development: a review and research agenda”, International Journal of Technology Management, Vol. 80 No. 1-2, p. 12-35.

Holmström, J. (2018), ‘Recombination in digital innovation: challenges, opportunities, and the importance of a theoretical framework’, Information and organization, Vol. 28 No. 2, pp. 107-110.

Huang, P.M., Darrin, A.G. and Knuth, A.A. (2012), ‘Agile hardware and software system engineering for innovation’, Proceedings of the 2012 IEEE Aerospace Conference, Big Sky, MT, March 3-10, pp. 1-10.

Joglekar, N.R. and Rosenthal, S.R. (2003), ‘Coordination of design supply chains for bundling physical and software products’, Journal of Product Innovation Management, Vol. 20 No. 5, pp. 374-390.

Karlsson, C. and Lovén, E. (2005), ‘Managing new technology integration: integrating software in manufactured products’, International Journal of Innovation Management, Vol. 9 No. 3, pp. 343-370.

Karlström, D. and Runeson, P. (2006), ‘Integrating agile software development into stage-gate managed product development’, Empirical Software Engineering, Vol. 11 No. 2, pp. 203-225.

Könnölä, K., Suomi, S., Mäkilä, T., Jokela, T., Rantala, V. and Lehtonen, T. (2016), ‘Agile methods in embedded system development: multiple-case study of three industrial cases’, Journal of Systems and Software, Vol. 118, August, pp. 134-150.

Kuwashima, K. and Fujimoto, T. (2013), ‘Performance measurement in product development research: A literature review’, Annals of Business Administrative Science, Vol. 12 No. 4, pp. 213-223.

Lee, J. and Berente, N. (2012), ‘Digital innovation and the division of innovative labor: Digital controls in the automotive industry’, Organization Science, Vol. 23 No. 5, pp. 1428-1447.

Lwakatare, L.E., Karvonen, T., Sauvola, T., Kuvaja, P., Olsson, H.H., Bosch, J. and Oivo, M. (2016), ‘Towards DevOps in the embedded systems domain: why is it so hard?’, in Sprague, R.H. and Bui, T.X. (Eds), Proceedings of the 49th Annual Hawaii International Conference on System Sciences, HICSS 2016, University of Oulu, pp. 5437-5446.

Maleki, E., Belkadi, F. and Bernard, A. (2017), ‘Systems engineering as a foundation for PSS development project: Motivations and perspectives’, in McAloone, T.C., Tseng, M.M., Mortensen, N.H., Shimomura, Y. and Pigosso, D.C.A. (Eds), Proceedings of the 50th CIRP Conference on Manufacturing Systems 2017, Ecole Centrale de Nantes, Nantes, pp. 205-210.

Nambisan, S., Lyytinen, K., Majchrzak, A. and Song, M. (2017), ‘Digital innovation management: Reinventing innovation management research in a digital world’, MIS Quarterly, Vol. 41 No. 1, pp. 223-238.

Porter, M.E. and Heppelmann, J.E. (2015), ‘How smart, connected products are transforming companies’, Harvard Business Review, Vol. 93 No. 10, pp. 96-114.

Siggelkow, N. (2007), ‘Persuasion with case studies’, Academy of Management Journal, Vol. 50 No. 1, pp. 20-24.

Svahn, F. and Henfridsson, O. (2012), ‘The dual regimes of digital innovation management’, Proceedings of the Annual Hawaii International Conference on System Sciences, Maui, HI, pp. 3347-3356.

Wacker, J. (1998), ‘A definition of theory: research guidelines for different theory-building research methods in operations management’, Journal of Operations Management, Vol. 16 No. 4, pp. 361-385.

Wolfenstetter, T., Böhm, M., Krcmar, H. and Bründl, S. (2016), ‘Why product service systems development is special’, in Framinan, J.M., Gonzalez, P. and Artiba, A. (Eds), Proceedings of the International Conference on Industrial Engineering and Systems Management, IEEE IESM 2015, Institute of Electrical and Electronics Engineers Inc, Seville, October 21-23, pp. 1221-1228.

Woodward, M.V. and Mosterman, P.J. (2007), ‘Challenges for embedded software development’, Proceedings of the 50th Midwest Symposium on Circuits and Systems, Montreal, Vol. 1-3, pp. 524-527.

Yin, R.K. (2009), Case Study Research: Design and Methods, 4th ed., Calif Sage Publications, Thousand Oaks, CA.

Yoo, Y., Henfridsson, O. and Lyytinen, K. (2010), ‘The new organizing logic of digital innovation: an agenda for information systems research’, Information Systems Research, Vol. 21 No. 4, pp. 724-735.

Yoo, Y., Boland, R.J., Lyytinen, K. and Majchrzak, A. (2012), ‘Organizing for innovation in the digitized world’, Organization Science, Vol. 23 No. 5, pp. 1398-1408.

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APPENDIX B. HENDLER (2019)

Appendix C. Hendler (2020)

Hendler, S. (2020), 'Exploring coordination practices in digital–physical product development', Journal of Manufacturing Technology Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/JMTM-06-2019-0229

Exploring coordination practices in digital-physical product development

Abstract

Purpose: The paper explores coordination practices in digital-physical product development and their consequences for companies traditionally relying on physical product development.

Design/methodology/approach: Using an embedded case study design, the paper reports four action research initiatives addressing the digital-physical coordination challenges encountered by a leading B2C company.

Findings: Effective coordination of digital-physical product development, firstly, involves standardization of process, output and skills to accommodate the stability needed for efficient physical product development and manufacturing. Secondly, it involves agile coordination events, such as Scrum ceremonies and PI planning, to facilitate the mutual adjustment needed to allow agility and the differences between digital and physical product development to be continuously and successfully negotiated.

Research limitations/implications: The paper illustrates a research model with case evidence and suggests tentative theory in the form of propositions. Future research should explore coordination problems and solutions in different digital-physical project types and contexts.

Practical implications: Coordination practices for digital-physical product development are presented and analyzed, providing inspiration for companies.

Originality/value: The paper is the first to explore coordination practices within the emerging field of digital-physical product development.

1 Introduction

Public bins that know when they need emptying, shoes that can control the temperature of your feet and Internet of Things enabled manufacturing equipment are examples of the increasing digitalization of physical products (Yoo, 2010; Porter and Heppelmann, 2015). Here, digital refers to software, and physical to tangible products without software. Such digital-physical products can range from a tangible product, e.g. a book, *accompanied* by a smart phone app in which the digital physical combination merely happens during product usage, to tangible products with *built-in* sensors, actuators and electronics, onboard firmware, software and a graphical user interface. Adding digital affordances such as programmability and shareability (Yoo, 2010) to physical products can significantly differentiate and enhance a product's value. At the same time, product digitalization challenges a manufacturer's operations along the entire value chain (Porter and Heppelmann, 2015). This includes the manufacturer's product development (Svahn and Henfridsson, 2012), which must coordinate the efforts of two essentially different development disciplines, i.e. software development and tangible product development, to deliver a successful digital-physical product.

Digital and physical product development literature has evolved relatively separate from each other (Nambisan and Wilemon, 2000; Karlsson and Lovén, 2005; Svahn and Henfridsson, 2012) and involve significantly different practices, as shown by Boehm and Turner (2004), Svahn and Henfridsson, (2012), Hendler and Boer (2019) and Hendler (2019).

Relative to physical product development, digital development can be described as adaptability-optimized with short, iterative development cycles, late binding or lock of the product's specification, several releases per product, and (near) zero materiality (Boehm and Turner, 2004; Svahn, 2012). In contrast, physical product development is more stability-optimized with one long development cycle, early binding, extensive up-front planning and one launch per product (Boehm and Turner, 2004; Svahn and Henfridsson, 2012). Inspired by Hendler's (2019) example from a successful developer and manufacturer of B2C digital-physical products, Figure 1 depicts the long physical front-end and development process leading up to launch with early binding before handing over to manufacturing. In contrast, digital development prefers later binding for many design decisions to stay responsive to new learning until launch, and keeps evolving the product after launch.

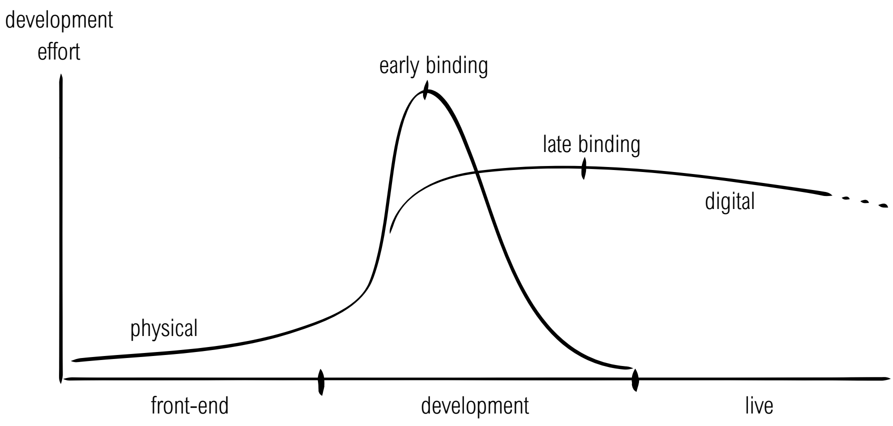

Figure 1 Digital versus physical product development

The problems of combining the adaptability and stability optimized processes have been illustrated in several case studies. Hendler (2019) describes an example where the manufacturer's early binding of the packaging design (optimized for production stability and efficiency) required the software vendor to supply screenshots from the digital experience to go on the packaging. As no digital consumer experience was available yet, the digital vendor had to approximate a screenshot based on uncertain predictions. Consequently, the vendor had to ignore valuable learning from the subsequent digital development to avoid misalignment with the packaging graphics. Other challenges include imposing an early and extensive planning phase upon the software development process (Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund and Bosch, 2012; Eklund et al., 2014; Lwakatare et al., 2016), the need for information of different levels of detail at different times in the process (Karlström and Runeson, 2006), and releasing "old" software at project launch as the digital development was aligned with the physical development's early binding (Eklund and Bosch, 2012). Addressing these combination challenges caused by the above differences between digital and physical development practices, Hendler (2019) proposes: "*When combining a physical stability-optimized ... and a digital adaptability-optimized development process, either the former must become more adaptable, the latter must become less adaptable or both need to change, which may reduce the performance of one or both subprocesses but should lead to optimal performance of the overall process.*" Several case studies show how software development typically compromises the most and goes some way to adapt to the physical development process (Joglekar and Rosenthal, 2003; Karlström and Runeson, 2006; Rottier and Rodrigues, 2008; Eklund and Bosch, 2012; Eklund et al., 2014; Cooper, 2016).

Many of these reports are based on cursory evidence. There is some literature on how to develop complex products, cyber-physical or product-service systems, which focuses on topics such as multi-disciplinarity, modularity and systems engineering (e.g. Wolfenstetter et al., 2016; Bialasiewicz, 2017; Maleki et al., 2017). However, theory that explicitly problematizes digital-physical development process is scarce and immature (Nambisan et al., 2017; Holmström, 2018). In this research, product development refers to the process of "transforming ideas into commercial outputs" (Hansen and Birkinshaw, 2007). In digital-physical development, products with both digital and physical components are developed in a combined digital-physical development process consisting of interdependent digital and physical development subprocesses. The question on how to effectively combine and manage the digital-physical product development subprocesses has hardly been explored (Hendler and Boer, 2019). Hendler (2019) deduces three supplementary strategies that can be used to effectively combine the digital and physical product development subprocesses: 1) reduce the differences between the two subprocesses, 2) combine the two subprocesses using appropriate coordination practices, and/or 3) create new development practices and a suitable development context. This research focuses on strategy 2 and manufacturing companies, which are digitalizing their products but have relatively little experience with software development. The research objective is:

To explore coordination practices in digital-physical development and their consequences for companies traditionally relying on physical development.

An embedded case study involving four action research initiatives is used to investigate this objective. The research takes a starting point in a tentative research model (Figure 3) proposed by Hendler and Boer (2019) and inductively illustrates some of the model's key constructs and relationships. The research proposes tentative theory on the emerging phenomenon of digital-physical product development in the form of propositions.

Section 2 provides the theoretical background. Section 3 accounts for the research method. Section 4 presents the case study data and proposes several propositions. Section 5 discusses the results and Section 6 presents the conclusion and discusses the limitations and options for further research.

2 Background

In the 1990s with software products growing in size and complexity and customer needs changing rapidly, agile development with its short, iterative and incremental build-test-learn cycles successfully replaced the prevailing best practice stage-gate model (Rigby et al., 2016). Physical product development, in contrast, remained less uncertain and its physical materiality and use of established process technologies made short iterations too costly (Hendler, 2019). With these contingencies, linear stage-gate development processes remained the dominant practice (Lenfle and Loch, 2010; Svahn, 2012). More recently, with manufacturing companies experiencing rapid digitalization of their operations and products, interest in agile-inspired project management practices has grown (see e.g. Conforto et al., 2014; Heeager, 2016; Rigby et al., 2016). However, the different characteristics (Boer and During, 2001) and materialities of digital and physical development requires different ways of managing them (Hendler, 2019). That different systems require different management approaches is also known from e.g. organization theory, e.g. mechanistic versus organic management systems (Burns and Stalker, 1961) and from the management of complex projects (see e.g. Lenfle and Loch, 2010), who observe that uncertain parts of a project need to be managed differently from the predictable parts. Such a managerial 'divide and conquer' strategy, however, involves careful consideration of how to coordinate the separately managed parts, especially if there are significant interdependencies between the two subprocesses (Thompson, 1967).

Similarly, digital and physical product development are usually managed differently (e.g. Boehm and Turner, 2004 and Svahn and Henfridsson, 2012). However, little theory exists on how to coordinate digital-physical product development subprocesses effectively (Svahn, 2012; Nambisan et al., 2017; Holmström, 2018; Hendler and Boer, 2019). To develop further insight into the coordination of digital-physical product development, relevant coordination practices from, first, adjacent bodies of theory, including organization, innovation, and digital as well as physical product development theory are presented below. Subsequently, examples and suggestions for digital-physical coordination practices, primarily based on case studies, are described. Finally, the research model is described.

2.1 Coordination

From a contingency perspective, Hendler and Boer (2019) finds that the process of "*digital-physical product development is characterized by a mixed materiality and a high degree of complexity, diversity, interdependence and uncertainty*". Uncertainty is the extent to which people are informed about the future. Complexity refers to the difficulty with which the work can be understood. Diversity denotes the variety of the work that needs to be done in terms of the number of different competences needed to perform a process. Interdependence is the extent to which (groups of) people depend on one another for their output (Boer and During, 2001). A digital-physical development process is more diverse and interdependent than pure physical or digital development processes. The combined process requires more different competences and, thus, the involvement of more different organizational functions. In effect, there are more interdependencies to coordinate. Examples of such organizational interdependencies include architectural, functional and esthetical design decisions that impact both digital and physical product design, and cross-subprocess scheduling to ensure timely digital-physical component integration. Several case studies on digital-physical product development do indeed exemplify significant degrees of interdependencies in, for example, the development of cars (e.g. Svahn et al., 2015;

Mocker and Fonstad, 2018) and telecommunications (e.g. Könnölä et al., 2016; Martini et al., 2016).

Hendler (2019) summarizes a number of characteristics and practices, which may complicate the coordination of the two processes (see Table 1). Specifically, she finds that compared to physical product development, the digital development process is characterized by a higher degree of uncertainty, a lower degree of diversity and materiality, which allows for an adaptability-optimized development process. Relatively, digital development is characterized by a lower degree of uncertainty, a higher degree of diversity, and a physical materiality, which allows for a stability-optimized development process.

Accordingly, digital development practices are described by short, iterative development cycles with predominantly cross-functional teams, empowered decision-making, one product vision holder, a floating scope, late binding, short up-front planning and several releases per product. Physical development practices are described by one long development cycle with a large extent of functional unit grouping, hierarchical and consensus driven decision-making, multiple product vision holders, a highly formalized and high-level, schedule-bound development process, early binding, extensive up-front planning and one launch per product.

Table 1 The relative characteristics and different practices and of digital, physical and digital-physical product development to the extent that theory is available

Relative measures	Digital development	Physical development	Digital-physical development
Diversity	Low	High	Higher
Uncertainty	High	Low	Higher
Complexity	High	-	Higher
Interdependency	-	-	Higher
Materiality	Immaterial	Material	-
Development cycles	Many, short (weeks)	One, long (years)	-
Project organization	Cross-functional	Functional	-
Decision-making	Empowered	Hierarchical and consensus driven	-
No. of product vision holders	One product vision holder	Multiple product vision holders	-
Scope development	Floating scope	Fixed scope	-
Binding timing	Late binding	Early binding	-
Planning approach	Short up-front planning and emergent (at least partly)	Extensive up-front planning and schedule bound	-
Output	Several releases per product	One launch per project	-

2.1.1 Intra-firm coordination

Mintzberg (1979) proposes a continuum of coordination mechanisms. Which mechanism is most suitable is contingent on the size of a group and the complexity and uncertainty or, expressed in terms of Perrow (1967), analysability and variety (Figure 2) of its task. The coordination mechanism mutual adjustment refers to the coordination between members of a small group performing either a simple, predictable, analysable and low-variety (i.e. routine), or a highly complex, uncertain, non-analysable and high variety (i.e. non-routine) task. Direct supervision refers to the coordination by a manager of a larger group conducting a relatively simple and predictable task. Standardization of work, i.e. the work process, is suitable for coordinating large groups performing a still relatively simple and predictable task. Standardization of output can suitably coordinate a smaller group performing a more complex and less predictable task. Finally, standardization of skills coordinates an even smaller group performing an even more complex and less predictable task.

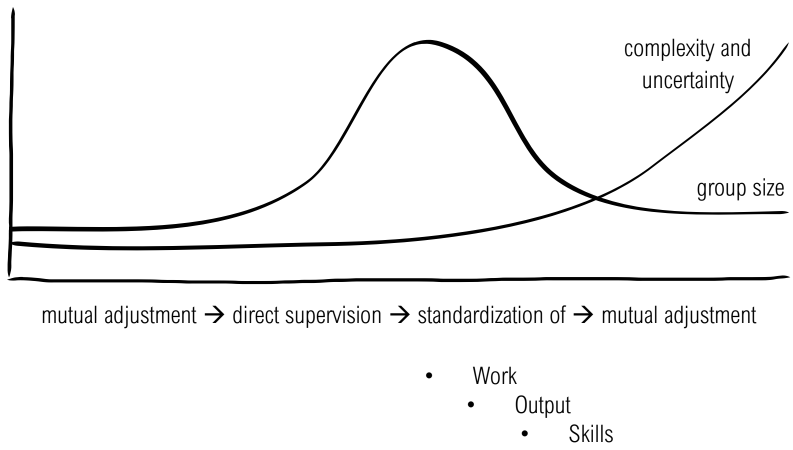

Figure 2 A contingent continuum of coordination mechanisms (inspired by Mintzberg, 1979)

These coordination mechanisms can be implemented through a wide variety of, what we call, coordination practices. Galbraith (1973) proposes an information processing view and suggests two practices reducing the need for information processing, namely the creation of slack resources and self-contained tasks, respectively, and two practices increasing the capacity to process information, namely investment in vertical information systems and the creation of lateral linkages. Daft and Lengel (1986) propose seven coordination practices along a continuum with respect to their relative capacity for reducing uncertainty, i.e. lack of information, and equivocality, i.e. ambiguity of information. The continuum ranges from impersonal rules and regulation (high uncertainty reduction, low equivocality reduction) through formal information systems, special reports, planning, direct contact, to integrator and team meetings (low uncertainty reduction, high equivocality reduction). Daft (e.g. 1992, 2004) distinguishes between paperwork, information systems, direct contact, liaison roles, task forces, full-time integrators and teams.

Paashuis and Boer (1997) consider that coordination can be achieved not only through organizational mechanisms and propose four categories of, what they label, integration mechanisms: integration by strategy, process, technology and organization. Integration by strategy refers to the setting of goals, which give a "*sense of direction to employees, motivate them, act as guidelines for decision making, and provide a standard for assessment*" (p. 83). Integration by process involves "*eliminating activities that do not add value, and simplifying and, if possible, integrating (also organizationally) or even automating (technologically) remaining activities*" (p. 83). Technology refers to humanware (the knowledge, skills and experiences of people), software (tools, methods and techniques that people use to perform their tasks, such as Quality Function Deployment or planning tools) and hardware (e.g. plant and equipment) that can all enable, or reduce the barriers to, coordination. Finally, integration by organization refers to the structural and cultural arrangements organizations use to coordinate people. Well-known practices include role combination, secondment, co-location, matrix structures, and standing committees (e.g. Mintzberg, 1979).

2.1.2 Inter-firm coordination

Considering inter-firm coordination may be relevant when a manufacturer is digitalizing in collaboration with external partners. Prencipe et al. (2003) state that in order to coordinate across organizational boundaries, companies need to know more than what is seemingly required, which increases the need for coordination. Lakemond et al. (2006) find that differences in project management methods, the existence of different types of constraints in product design and long-term inter-firm collaboration objectives also increases the need for coordination. Hong et al. (2009) considers the locus of decision-making when designing inter-firm coordination. Decentralized decision-making involves e.g. mutual adjustment, formal documentation, liaison roles and division of labor; centralized planning, review and control mechanisms, and inter-firm team meetings are examples of centralized decision-making. "*When using a centralization strategy, a manufacturer would maintain control over decisions, such as critical engineering decisions, detail design, material choice, and supplier selection. With a decentralization strategy, decision-making authorities are dispersed, information is segregated, and actors are geographically dispersed*" (Hong et al., 2009, p. 1008).

2.1.3 Coordinating physical product development

Hendler and Boer (2019) finds that relative to physical development, digital development is more uncertain and less diverse. Accordingly, most product development processes of pure physical manufacturers today rely on some form of plan-driven process aiming for high levels of stability and predictability, often a version of the stage-gate model proposed by Cooper (1990). Although Cooper (2008) later updated and clarified its intention as a flexible process map based on what winning teams do, its implementation typically involves a rigid control and delivery process in which the development process is organized and managed as a project. The coordination largely relies on traditional mechanisms, in particular meetings and teamwork. Adler (1995), Swink (1999) and Vandevelde and Van Dierdonck (2003) see positive effects from development team integration processes that can elevate the voice of downstream stakeholders. Vandevelde and Van Dierdonck (2003) emphasize the need for formalization to facilitate an efficient production start-up. Adler (1995) describes the need to adjust the coordination mechanisms under varying conditions of uncertainty and equivocality throughout the product development phases and proposes using more intensive coordination methods such as mutual adjustment or teams when novelty is high. The gates are manned by a, typically multidisciplinary, multifunctional and senior, "gatekeeping group" (Cooper, 1990, p. 46). The stages are driven by a project leader, who is responsible for organizing the project team and delivering the inputs assessed at the gates.

More recently, Cooper (2016) proposed "*blending agile and stage-gate methods [to] provide flexibility, speed, and improved communication in new-product development*" (p. 21), and noted that "*the early evidence, albeit quite limited, is encouraging*" (p. 28).

2.1.4 Agile coordination practices

Agile development includes several coordination practices as part of a meta-process that facilitates effective learning within and across teams. This learning builds on the three agile pillars of transparency, inspection and adaptation, which enable ongoing process control (Schwaber and Sutherland, 2017).

Common coordination practices, known from some of the most popular process frameworks such as Scrum (Sutherland, 2015), Large Scale Scrum (LeSS) (Larman and Vodde, 2016) and the Scaled Agile Framework (SAFe) (Knaster and Leffingwell, 2017), coordinate teams of five to nine people or teams of teams of up to 150 people. Agile coordination practices include daily stand-ups with Scrum or Kanban boards, cadenced sprint planning including goal setting, sprint output reviews and retrospective meetings, release planning, co-located, self-contained teams, on-site customers, coding standards, collective ownership of team output, program increment planning (PI planning) to plan across multiple teams and sprints, cadenced product owner meetings to ensure product vision alignment, and shared principles and values such as empowerment. A key purpose of these predominantly horizontal coordination practices is to allow rapid adaptation to new learning while adhering to a stable and proven process framework (Sutherland, 2015). Another popular agile framework is Scrumban, which allows a team to change priorities as soon as resources become available, whereas Scrum only changes priorities in a fixed cadence (Kniberg and Skarin, 2009).

2.2 Coordinating digital-physical product development

Some authors propose using a stage-gate approach for the combined development process. However, the stage-gate process predominantly benefits the physical process; adopting that approach to manage the digital development process goes at the expense of adaptability (Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund and Bosch, 2012; Eklund et al., 2014; Lwakatare et al., 2016).

Other authors suggest agile methods with short, joint, iterative development cycles (Könnölä et al., 2016; Eklund and Berger, 2017) to coordinate the overall digital-physical development process. However, this practice has its drawbacks, too, in the form of challenges concerning team composition (Könnölä et al., 2016; Eklund and Berger, 2017), and task management flow, due to many non-interchangeable competences, and digital preferring shorter cycle times compared to physical (Könnölä et al., 2016).

Thus, both stage-gate and agile coordination have benefits and disadvantages, and more research is needed to explore options to maximize the benefits and reduce the disadvantages. A blended agile stage-gate approach (Cooper, 2016) could be one such option. Hendler (2019, p. 327) agrees: "*In order to achieve a performance gain from combining the digital and the physical product development processes, managing the trade-offs between these processes requires close collaboration and effective communication.*"

2.3 Analytical model

For this research, we take our starting point in a simplified version of the research model proposed by Hendler and Boer (2019) (Figure 3).

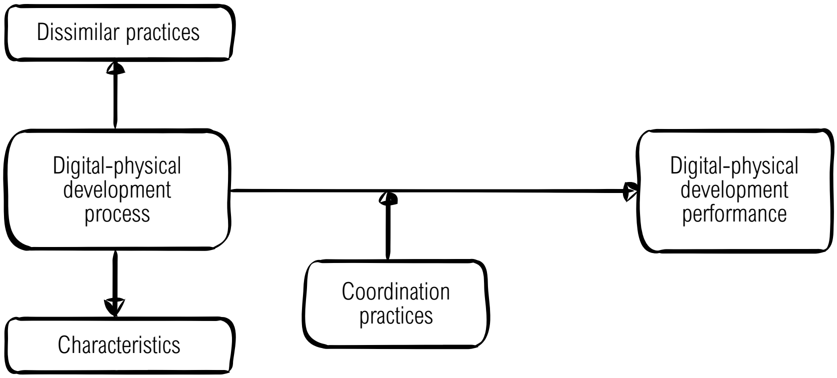

Figure 3 Analytical model (adapted from Hendler and Boer (2019))

The model presents three key constructs: *digital-physical development process, coordination practices* and *digital-physical development performance*. The *development process* include the digital and physical development practices within the combined product development process, which are (partly) dissimilar due to different process characteristics, and consequently, different practices.

Combining these two sets of practices may affect development performance directly. Development performance refers to process criteria such as process cost and lead-time, and product criteria such as product quality, cost and performance (e.g. Kuwashima and Fujimoto, 2013). The digital-physical *coordination practices* are considered to moderate the relationship between the digital-physical development process and its performance.

3 Method

3.1 Case company

The case company, COMP, is a successful global manufacturer of B2C products. COMP employs 16,000 employees worldwide. Its activities include a mature and elaborate standard product development process with many parallel development subprocesses and more than 200 deliverable deadlines distributed amongst them. The process consists of two main phases: front-end and execution. The product development projects are organized with a small cross-functional project management team and a project organization consisting of representatives from numerous functional departments. In the first half of the execution phase, a pure physical project typically includes 25 people. Traditionally, COMP has focused on quality, risk reduction and schedule adherence to enable the manufacturing system, with a relatively long lead-time, to remain stable and profitable.

Supplementing an award-winning physical product development capability, COMP works with world class digital vendors. Over the past five years, COMP has invested in additional internal digital competences to support an increasing number of digital-physical projects and is building up a digital-physical product platform. More than five projects have successfully launched digital-physical products.

The research combines an embedded case study method with four units of analysis, with action research. The case study method allows exploring a complex and contemporary social phenomenon embedded in its context, while retaining its holistic and meaningful characteristics (Yin, 2009). Action research combines research with action and produces practical theory and solutions based on a series of learning loops (Coghlan and Brannick, 2010). The loops include the theory-testing problem solving approach of planning, action and fact-finding (Lewin, 1946). This combined method provides empirical evidence and deductively illustrates the research model (Figure 3) by giving specific examples illustrating the conceptual constructs and their relationships (Caniato et al., 2018).

3.2 Four embedded action research cases

Functioning as a product development management consultant and certified agile coach with an existing relationship with COMP, the author had the opportunity to collect data, analyse COMP’s digital-physical coordination problem, and develop and test solutions via action research. COMP’s inability to effectively and efficiently coordinate the work across multiple subprocesses in the uncertain projects, had resulted in dissatisfaction among project team members and product quality problems, including unrealised product features, device compatibility issues, and other technical problems. COMP, however, lacked the background (theory, experience) needed to understand and solve the problem. Exploiting this opportunity, data was collected from two process documentation efforts, hereafter labelled *Process w/o hw* and *Process w/ hw*, and two product development projects, *Project D* and *Project E*. See Table 1 for data collection details. These four efforts were a result of a convenience sampling, presenting themselves as highly relevant opportunities for action research, with no other formal initiatives easily accessible to the action researcher.

Process w/o hw started in March 2017 to update the standard product development process description reflecting on and addressing key challenges regarding digital-physical projects. The result was a process description of one additional subprocess aimed at developing a software component to work in consort with a physical product using 3rd party devices.

Process w/ hw started in April 2018, aimed at developing key capabilities needed to more efficiently and effectively run highly complex digital-physical projects including a physical product complemented by software, firmware and hardware. Hardware refers to the electronics with the required input and output components, such as sensors and actuators, needed to digitalize the otherwise non-digital product. This process description adds up to six subprocesses to a project and includes both internal and external development. Both process documentation initiatives were managed, facilitated and documented by the action researcher. The documented process solutions were devised in collaboration with COMP employees and, in workshops, tested against the experience obtained from four recent digital-physical projects.

Project D started early 2017 and was aimed at developing a highly innovative digital-physical product allowing new user journeys and applying new digital-physical product integration mechanisms by using state-of-the-art, externally developed software in the form of a mobile device app. Similar to *Process w/o hw*, no hardware or firmware was developed. Nevertheless, the project included around 50 people in the first half of the execution phase. The digital and physical components are integrated in the hands of a user through 3rd party devices such as smartphones and tablets. The physical product is used together with the information provided by the app in which the physical product is mirrored and modified. An example of a product with a similar digital-physical integration could be a high end comic book that allows you to scan individual pages with a mobile phone, which then adds sound effects while you read the individual pages, and mirrors the pages to add new characters in them that an author had originally intended. The COMP project resulted in much higher levels of diversity, complexity, uncertainty and interdependency in comparison to the company's pure physical projects. For example, the first half of the execution phase required continued product exploration due to large uncertainties, and the diversity was evident with a total of nine subprocesses that needed to be coordinated across many functions. The project successfully tested several new digital-physical development coordination practices. Co-located with the project team for three months, the action researcher functioned as an agile management consultant in a team of two coaches, predominantly helping the project management team designing appropriate coordination mechanisms, and preparing and facilitating various agile coordination events, while capturing and sharing learning.

Project E was another product development project that started late 2017. It was less innovative compared to Project D as it built on platform technology and product usage patterns developed for a previous digital-physical project. However, the project included both internally developed hardware, software and firmware as well as externally developed software in the form of an app. Hence, compared to Project D, Project E was more diverse and with a higher level of interdependency between the many product components. The project was less uncertain compared to Project D, but nevertheless much more uncertain than the usual pure physical project. The digital and physical components are integrated in use through 3rd party devises as well as in the physical product via firmware, electronics, sensors and actuators. An example of a product with a similar digital-physical integration could be a baby cot that can soothe the baby through various rocking patterns and sounds via actuators, speakers, microphones and a smartphone app. Using the new practices proposed by the Process w/ hw initiative and learning from Project D, the project tested new practices focused on the coordination of digital and physical development across a total of fourteen subprocesses in the first half of the execution phase. The researcher functioned as an agile management consultant focused on solving the project's coordination problem, proposing new practices, coaching the project management team during their implementation, and helped capture and share learning from the new practices. The solutions in both Project D and E were strongly inspired by agile, innovation and organization design literature (see Section 2) presented by the action researcher in a number of workshops and meetings and adapted to fit the specific project context.

All four action research initiatives contributed with solutions for how to coordinate digital-physical product development projects. The process documentation initiatives provided standards for future digital-physical product development projects to help anticipate and design needed coordination practices. The digital-physical development projects tested the new process documentation and additional new coordination practices.

3.3 Data collection

The action research loops were conducted as an integrated part of the development and implementation of the new agile practices. That is, the planning of new coordination practices was initially conducted in project management meetings. Next, the new practices were implemented by the project management, in close collaboration with the action researcher and another agile coach. Based on continuous fact finding (through data collection and analysis), new action was planned and implemented to adjust the new coordination practices as and when required. The data from the four initiatives was collected through documents, facilitation of, or participation in, multiple meetings, including sparring meetings between the project management and the agile coach, workshops, sharing events, formal interviews and informal conversations (see Table 2), and a survey (see below). Notes on observations and contextual changes, reflections on the observations and options for future actions along with photos of e.g. meeting scribbles were captured in the action researcher's diary (cf. Coghlan and Brannick, 2010) and summarized in formal and shared event summaries where appropriate. To help design the workshops in the two process documentation initiatives, a formal interview was conducted early on in each initiative, focused on the difficulties experienced in recent digital-physical projects (see Table 2).

Table 2 Overview of the collected data

Process w/o hw	Process w/ hw	Project D	Project E
Data collection period			
2017 March-October	2018 April-October	2017 June – 2018 October	2018 April – October
Key stakeholders			
With experience across 4 digital-physical projects: 5 x Project managers 4 x Digital producers	With experience across 3 digital-physical projects: 4 x Project managers 2 x Hardware engineer/manager 2 x Firmware engineer/manager 3 x Digital producers 1 x Technology manager 1 x Quality manager	Project team	Project team
Key events			
• April: Workshop (2h) identifying key digital-physical project challenges • May: Workshop designing new process description based on prepared draft	• March: 2-day workshop designing new processes, roles and governance models • June: 4 workshops (1-2 h each) to mature new process	• December-March: 2 week sprints for selected project areas • February: Review meeting of project practices • February: 4-day kick-off workshop with external	• June: 4 workshops (1-2h each) defining new ways to manage and coordinate the project efforts • July – October: 4 week sprints

• June: Review of process documentation • October: Review of process documentation	• April – June: bi-weekly coordination and work meetings focused on new governance models, roles and implementation	digital partner • April: Larger retrospective reflection upon agile practices • May: Start bi-weekly agile planning and dependency mapping	• October: Full day workshop to share new practices from Process w/ hw and Project D with other key stakeholders
Collected data			
• Action research diary (6 pp.) • Description of digital-physical process challenges • Digital-physical process description with roles and key integration points • Informal conversations with project management and project members across four digital-physical projects • 1x interview (1h) with digital-physical project manager • Summary of digital-physical challenges from previous projects	• Action research diary (31 pp.) • Description of challenges in digital-physical with hardware projects • New process description of product development and post launch phases • Workshop summaries and photos of post-its and white board drawings • 1x interview (1h) with digital-physical project manager	• Action research diary (191 pp.) • Summaries of Scrum events (planning, review and retrospectives) • Project management project documentation incl. plans and team overviews • Survey data on planning and dependency mapping effectiveness • 6x interviews (1h each) with digital-physical project coordinators	• Action research diary (32 pp.) • Workshop summaries and photos of post-its, posters and white board drawings • Survey data on planning and dependency mapping success • 7x interviews (1h each) with digital-physical project coordinators

Thirteen formal interviews structured around six open-ended questions were performed with the digital-physical project coordinators of projects D and E (see Table 2). To best illustrate the research model (see Figure 3) the questions were aimed at exploring the implemented coordination practices, the reasons behind these choices (the project management chose which practices to implement, not the action researcher) and their consequences.

1. What is your background – digital/physical/mix?
2. Is digital-physical coordination something you are extra aware of? If yes, why?
3. How are you making sure that the digital and the physical development stay aligned toward delivering an integrated experience, i.e. which different coordination practices do you use?
4. Why have you chosen these coordination practices and to what extent are they successful?
5. Can you mention specific examples of a need to 'negotiate' or make trade-offs between physical and digital development needs? How have these specific 'negotiations' been made?
6. What would be your recommendation for digital-physical coordination in future projects?

In addition, a survey with five statements using a five-point Likert scale was answered by the Project D and E teams to validate observations on the effect of the new, less controlled agile coordination practice with dependency mapping, which was considered to put the project at risk in terms of potential planning oversights and wasted time.

1. The monthly/bi-weekly sprint planning sessions are enabling better planning (compromises and solutions) compared to typical project planning sessions.
2. The sprint planning meetings are helping the project to better adapt to unforeseen challenges.
3. This is a valuable project management tool for projects with a similar or higher uncertainty profile.
4. I have felt the meetings have been worth my time.
5. Comments

3.4 Data validation

Data triangulation was ensured through comparison with additional documentation including product concept visuals, project planning boards, organization charts and project charters. Further triangulation was done via frequent interaction with multiple project stakeholders across the four initiatives, all within the same product development organization. The consultant role already presents a research type role and has a lower risk of role-duality conflicts (Coghlan and Brannick, 2010). In this case it involved a preunderstanding of the inner workings and culture of COMP's product development organization as well as a need to maintain a strong professional relationship.

However, being too close to the data can be a disadvantage (Coghlan and Brannick, 2010). Hence, biases and preunderstandings were sought mitigated via a reflection space in the research diary considering 'group think' dynamics and 'what-I-think-I-know' risks (Coghlan and Brannick, 2010). Examples from such reflections in the diary include "*... the resulting agility may not be as significant as we think*" (Diary 26.02.2018) or "*A survey to capture the performance effect of the dependency mapping would certainly be in place. ... When I approach participants, they seem eager to praise the idea, maybe to be kind*" (Diary 04.09.2018). Taking on the researcher role, interviews were executed in a more objective style. Finally, a COMP employee and former digital-physical project manager, knowledgeable about the new coordination practices in projects D and E, read this paper to formally approve it from the perspective of COMP, and ensure quality and non-disclosure of confidential information.

3.5 Data analysis

The data analysis first involved reviewing the collected data regarding the three constructs: coordination challenges, coordination practices and their performance effects. For each of the four initiatives the extracted key information was condensed into summary or interview statements and transferred to spreadsheet columns, one for each of the three constructs, and placed in rows according to categories emerging based on similar coordination challenges and practices, such as 'lack of co-location', 'differences in language and knowledge' and 'bi-weekly project reviews'. The categories were further grouped into wider categories, such as 'dependency mapping' and 'visual process communication', and conclusions were drawn, first within each initiative and, then, across the four initiatives. The effects of the coordination practices were measured in terms of the ability to create ongoing digital-physical goal clarity, digital-physical transparency, inspection, frequent feedback, and learning, which, based on COMP's previous digital-physical development experience, impact process performance. Finally, propositions were formulated.

4 Results

With a starting point in Mintzberg's (1979) coordination mechanisms, this section analyses the empirical data in the light of the constructs and relationships presented in the research model. Section 4.1 analyses the characteristics, or contingencies, to which the coordination mechanisms, and the specific practices through which these mechanisms are implemented, must be fitted. Section 4.2 analyses the new coordination mechanisms and practices proposed in the four action research initiatives and implemented by projects D and E. Propositions are formulated based on the performance consequences.

4.1 The digital-physical coordination contingencies

In order to cope with a large project group size including many diverse functions throughout the course of a project, COMP's primary coordination practices for its pure physical projects of, typically, low uncertainty include following elaborate process standards and early planning of detailed deliverables up to one year ahead. Many product components are largely developed in local departments following their development subprocesses and local priorities, enabled by mature product platforms. Subprocess drivers meet in weekly project status meetings where they report potential schedule deviations. The project manager also coordinates via email and one-to-one meetings.

The digital-physical product development projects challenged COMP's normal project coordination mechanisms significantly. First, they presented high degrees of diversity and interdependence due the inclusion of one (Project D) or up to six (Project E) new digital development subprocesses. In the first half of the execution phase the software and firmware development started along with the development of many downstream resources such as packaging graphics, instruction leaflet design and marketing. The increased interdependency was caused by the digital product part(s) influencing these resources as well as the physical product design and, for example, also the business model, marketing strategy and stock-keeping policy. The increased task diversity and interdependency resulted in a higher need for coordination. Additionally, the more radical product concept increased the project uncertainty, especially in the first half of the execution phase, due to many new digital-physical interdependencies and the uncertainty from the digital development migrating to the physical development subprocess. As stated by a Project D member, "*... most of the schedule uncertainty comes from digital*". Unable to deal with the many and uncertain interdependencies and their timing, COMP's traditional and highly standardized product development process failed to facilitate the coordination needed. A project manager who just experienced a digital-physical project and its collaboration with multiple external and internal functions across digital and physical stated: "*we need to professionalize our capability when it comes to digital-physical projects*", and shared examples of stress, lack of transparency, quality errors and never realized product features due to the inability to coordinate and integrate all the software components into the final digital-physical product before launch. The project manager of Project E concluded: "*As we also know from previous projects, coordinating the various software components is the biggest challenge in this project: How to create full stack alignment?*".

With much interdependent digital-physical design work, the coordination was further challenged due to the different development cycles, i.e. early vs. late binding. COMP's physical development involved an early lock of physical design decisions. In Project E, the physical design was partially locked even earlier to allow more testing. In contrast, many digital design decisions were resolved much later: discovering the best possible digital product for the user is an incremental process, which does not stop until four weeks before launch and may continue until the product exits the market. The external digital vendor supporting Project E explained: "*We never think 'this is perfect' and are always open to improvements. That is why it is so important for us to stay agile.*" Finally, the firmware needed in Project E followed yet another schedule, as it needed to be ready for manufacturing and final product quality testing, which required it to be locked several months before launch, but four months later than the physical lock-in.

Project coordination was further challenged as COMP had few internal digital resources, even fewer staff who understood both digital and physical subject-matter aspects and language, and worked with state-of-the-art vendors who were located in different time zones (nine hours of difference in Project D; six hours in Project E). Also, differences in development and planning methods, in terms of language and underlying assumptions, complicated the coordination. Examples include planning with prioritized features and stories (digital) vs. man-hours and unprioritized deliverables (physical) or differences in planning principles such as deselecting features when time is running out (digital) vs. adding man-hours when time is running out (physical).

Finally, digital and physical development represent two different mindsets, which created coordination issues in itself. The project manager of Project E exemplified: "*Seeing the two different mindsets clash has been interesting. ... the traditional functions only ask for specific deadlines for when the finished version of their work is needed. However, the digital people reply with: 'When can we see some early work so that we can start collaborating?' and are ready to negotiate*".

In summary, the large number of interdependent and diverse subprocesses and product components, the higher project uncertainty predominantly coming from digital, and the differences between digital and physical development including different development cycle lengths, planning practices, language and mindsets forced COMP to change its project coordination practices in order to remain effective in its development processes.

Proposition 1a: The agility-optimized digital and stability-optimized physical development processes deploy different development cycle lengths (e.g. late versus early binding), planning practices (e.g. stories vs. man-hours), language and mindsets.

Proposition 1b: The uncertainty, diversity and interdependency of the combined digital-physical development process are higher than those of the individual processes.

Proposition 1c: The association between the combined digital-physical process and the performance of that process is moderated by the practices deployed to coordinate the digital and physical development subprocesses.

4.2 Coordination via standardization of process, outputs and skills

This subsection presents case evidence showing the effects of standardization on the project coordination success in projects D and E. COMP standardized two digital-physical processes, one with, and one without, hardware and firmware, by *fitting* the new software development subprocess to the stability optimized physical development subprocess. For both processes the minimum required digital skills, responsibilities, phases, deliverables and their integration points (which the employees refer to as milestones) were described. Continuing the logic from the existing physical process standard, all new digital deliverables were scheduled defining the latest time by which they must be delivered in order to not jeopardize overall project lead time and stability. The key purpose was to delineate processes that could help the projects plan, coordinate and build the confidence that it was possible to successfully combine the stability optimized physical development process including early binding with agile digital development processes. Given the high uncertainty of the digital-physical projects, the standards were not intended to serve as a mould for the projects, but as a shared default for *good practice* which, if followed, would allow comfortable adherence to the physical deliverables plan and allow efficient utilization of existing standard practices and manufacturing predictability. Thus, the projects were invited to use the documentation as a starting point for planning and coordination.

Both documented processes assume a highly uncertain and interdependent project. The key assumptions included that, if the (inter)dependencies between digital and physical would be clear up-front and the digital software vendor could start its production immediately after the front-end phase had ended (earlier than experienced in previous digital-physical projects), the digital development could adapt to the physical development by fitting a solution to the COMP-defined digital-physical concept.

4.2.1 Process w/o hw

This standardization initiative started in March 2017 by a group of internal project managers who, with recent experience from four finished digital-physical projects between them, wanted to find solutions to some of their shared problems. After a workshop it was concluded that 28 out of a total of 49 problems relating to digital-physical development could, a least partly, be addressed by developing a process standard. The process documentation included the execution phase only, the most challenging phase at the time.

4.2.2 Process w/ hw

A year after Process w/o hw had started taking shape, Process w/ hw was motivated by a group of managers and project employees who, based on a finished and an ongoing digital-physical project with hardware and firmware, were frustrated by COMP's inability to successfully accommodate these projects. One of the key problems concerned the ongoing coordination of many product components, ensuring successful integration into the end product, i.e. who is responsible for delivering what and by when? Also, an even earlier binding of the physical development was necessary to ensure more time for complex component integration and tests.

The resulting documentation covered the execution phase with five subphases and deliverables, which would help coordinate and ensure a synchronized progression of development maturity across all components. Especially one new integration point called ‘integrated experience approval’ was considered of high value, as it was placed in the latter half of the process, in which local component development in COMP traditionally was not very focused on product integration but rather on finalizing according to their subprocess standards.

4.2.3 Performance consequences

The project managers of projects D and E along with several other project members had been involved in the Process w/o hw and Process w/ hw initiatives, respectively, and the documentation was available in the beginning of both projects’ execution phase. Accordingly, Project E based their planning on the Process w/ hw documentation and, with this transparency, was able to make schedule adjustments up-front, optimizing physical stability and digital agility: “*We have less need for early binding in some areas, as we do not need to develop new hardware. ... We engaged the external digital vendor later in the process due to a lower uncertainty.*”

Project D’s manager quickly realized that: “*The documented process did not fit us, since we had much higher uncertainty and needed a much more exploratory process, albeit within the limits of the* [physical] *milestones. We decided deliberately not to follow large parts of the documented* [digital] *process* ... [and] *accepted much more project risk further down into the execution phase.*” Being aware that the project was less mature compared to the documented process helped the project to be more transparent and make better informed trade-offs between adaptability and stability, and the project manager shared later in the process: ”*We commit early to* [physical materiality]*! We have to work as a waterfall ... But we must be realistic and accept the digital vendor to do some learning about a narrower part of the solution first. It requires us to be very focused on the planning, be conscious of the trade-offs to make everything fit together and push much more risk in front of us. ... We are not just blindly following the milestones, but carefully evaluate the cost of delaying them when needed. However, we will always try to stick to the* [physical] *milestones*”.

The high degree of diversity and interdependency characterizing both projects meant that it was very important for the project managers to provide transparency to help the project members keep an overview, for which the process standardization provided an important baseline: “*It is important to help the room focus on the bigger picture and the high cost of delaying milestones so as to ensure that the dialogues are effective.*” The transparency from the process documentation work also facilitated a cross-digital-physical knowledge exchange including subprocess requirements and language.

Documenting processes with high uncertainty, i.e. lower repeatability, is challenging. Nevertheless, standardized integration points and deliverables provide support for the physical development stability while providing important information enabling informed stability-adaptability trade-offs by enabling central and local (in subprocesses) anticipation of (inter)dependencies and by visualizing schedule constraints.

Both Project D and E fulfilled their performance targets, and with high consumer ratings. Previous performance problems attributed to poor coordination, such as a lack of transparency and stress (see Section 4.1), were not a problem for these projects.

Proposition 2: Coordination through standardization of process (e.g. integration points), output (deliverables) and skills (roles, responsibilities) enables better informed stability-adaptability trade-off decision-making which, in turn, moderates the association between the combined digital-physical process and its performance.

4.3 Coordination via standardization of coordinating meta-processes and supplementing practices

The aim of this subsection is to present case evidence from projects D and E showing the effects of implementing new coordination mechanisms in terms of the standardization of new coordinating meta-processes to fit the new contingencies. In addition to the meta-processes, supplementing coordination practices used to implement and support the new mechanisms are analyzed. Table 3 presents an overview of these following the categorization by Paashuis and Boer (1997) in terms of strategy, organizational arrangements and technology.

Table 3 Coordination via strategy, organization and technology in projects D and E[1]

<table>
<tr><td colspan="2">Strategy
• Trust development subprocesses to do their own planning in the best interest of the full project
• Cadenced goal setting (D)
• Cadenced planning and negotiation focused on dependencies and integration
• Prioritize cross-functional learning
• Empowerment and transparency
• Focus on coordination practices and continuously adjust
• Exploit best practice agile coordination practices
• Clear digital-physical product integration design principles
• Use Scrum where most uncertainty (D)
• Fast, empowered product decision making and feedback by limiting amount of digital-physical decision-makers (E)
• Support cross-project learning and problem solving
• Effective ad hoc coordination over formalized and cadenced coordination where feasible for COMP-internal (inter)dependencies (E)</td></tr>
<tr><td colspan="2">Organizational arrangements
• Physical product and digital user experience design integrated in one development subprocess (task force) (E)
• Digital-physical liaison/translator role
• Digital-physical design pairs (D)
• One digital-physical design responsible (E)
• Digital design responsible in project management team (D)
• Broader and overlapping project roles
• Co-location and co-creation when feasible</td></tr>
<tr><td>Technology
<u>Humanware</u>
• Learning-motivated
• Digital-physical experience

<u>Hardware</u>
• Area for project co-location
• Wall space and white boards</td><td><u>Software</u>
• Agile and traditional plans
• IT sharing platforms for cross-digital-physical work
• Online meetings
• Visual and video messaging
• Scrum board
• Exploration Kanban board (D)
• Sticky note risk maps, dependency and project plans
• Team overviews</td></tr>
</table>

[1] (D) denotes: only in project D; (E): only in project E; all other items: both projects.

4.3.1 Project D: Coordination via Scrum

With more uncertainty than normal, Project D renamed the first half of the execution phase to 'the problem-solving phase', and set out to discover good ways of managing this phase, in which some subprocesses could nearly proceed as normal (optimizing for stability) while other work relating directly to the digital-physical concept included much exploration and, in effect, adaptability before design lock. The predominantly co-located digital-physical concept exploration team successfully tested Scrum practices during the first twelve weeks of the problem-solving phase. Figure 4 shows the implemented sprint events in a two-week cadence.

As the sprint events replaced the usual project status meetings, the full project team was invited. Thus, this new agile practice enabled focused progress monitoring and effective coordination of the full project based on transparency, by ensuring all were informed about the goals and the core activities of the project every two weeks and empowered to act accordingly via mutual adjustment. In the project reviews, all subprocesses could show relevant progress in the form of, for example, the latest digital prototype or the project manager showing the latest team overview. An exploration Kanban board helped manage issues or areas to explore. With the implementation of Scrum came the motivating mindset around learning, openness, trust and freedom to make empowered decisions. To ensure coordination towards integration points beyond the next two weeks, the project manager would present a sticky note project plan, based on the standardized process documentation, during the project review meetings.

The standardized Scrum events functioned as a meta-process, a process about the process, in which the full project was given the information to enable mutual adjustment. The project manager noted in relation to the Scrum cycle and the benefits of continuous goal setting: "*It is like kicking off the project every 14 days*." Scrum was appreciated by both the sprinting digital-physical team as well as other non-sprinting project members.

4.3.2 Project D: Coordination via SAFe inspired dependency mapping

After the first twelve weeks, the external digital vendor started its production process. This required a new way of organizing the project, as the locus of innovation and the key source of uncertainty was now moved to this vendor. COMP's initial digital-physical concept team was discontinued in its previous form and refocused on supporting the needs of the digital vendor. At the same time, the marketing campaign and other subprocesses were started up to work towards a design lock-in involving multiple digital-physical interdependencies. Scrum coordination was no longer suitable, as the project increased in size with more downstream resources and gradually changed its focus from exploration to execution across nine development subprocesses.

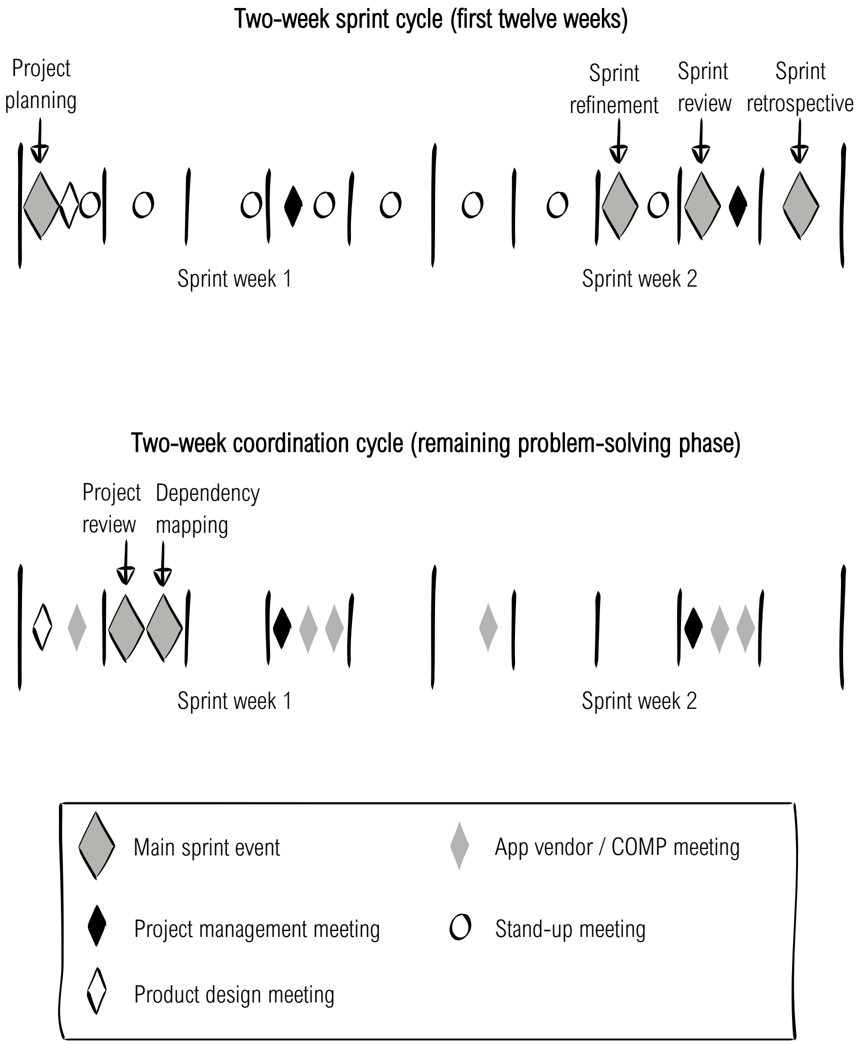

Figure 4 Project D's standardized meta-processes of coordinating events

To coordinate effectively and efficiently across different development methods, the agile PI Planning workshop was adopted from the SAFe toolbox (Knaster and Leffingwell, 2017). This tool facilitates different teams to coordinate their goals and dependencies using post-its and a swim-lane board showing teams on one axis and time increments in the other. To accommodate rapid learning from the digital development and the high project uncertainty, the PI Planning workshop was scaled down from one to two days to only one hour and held every two weeks instead of every eight to twelve weeks. At least one project member from each subprocess participated in the meetings which, however, often included 15 to 20 people. The meetings focused on dependency mapping and risks throughout the full project duration.

The dependency mapping meetings typically started with the project manager highlighting schedule risks and upcoming integration points. Then the participants self-organized in an informal manner to negotiate and document dependencies with sticky notes on the plans while documenting new risks or relating to existing ones. Finally, the project manager either concluded the meeting by asking the participants to summarize key changes to the plans or merely stating the end of the meeting, trusting the participants to mutually adjust as needed after the meeting. To ensure informed negotiations, the dependency mapping sessions were preceded by a one-hour project review, a continuation from the successful Scrum practices (Figure 4, the two-week coordination cycle).

As the digital vendor was in a different time zone, their work and epic/feature plans were represented by two COMP project members: the digital design responsible and the digital production responsible. Both had digital backgrounds. They often shared a demonstration video of the digital vendor's latest build in the project reviews and subsequently negotiated interdependencies using their in-depth knowledge of the vendor's work. The dependency mapping provided a space for joint learning about the project's subprocesses and constraints, enabling mutual adjustment.

4.3.3 Project D: Supplementing coordination practices

With the digital vendor in a different time zone, further cadenced and formalized coordination was implemented in the form of three online video meetings per week (Figure 4, the two-week coordination cycle). Two of the meetings evolved around prioritization, planning, dependencies and the removal of impediments; the third focused on the integration of the digital-physical product components with both physical and digital designers present. To further help this dialogue, digital and physical designers had been paired up in small task forces, each focused on one product variant. Involving email exchanges, working on shared design documents and video diaries via IT sharing platforms, the pairs' collaboration proved valuable. The digital vendor noted: "*the* [COMP] *designers wanted to design in the normal* [COMP] *way, but were not aware of critical* [digital] *constraints. This resulted in a lot of compromising, a lot of give and take…. Had we known all the* [physical] *design constraints in the beginning, it would have been a lot easier. But no one knew this when we started off; it was something we had to learn.*" To further improve the shared learning and coordination between the digital and the physical design efforts, representatives from the sites came together every two months with a focus on co-creation and goal setting. Also, digital and physical design responsibles met every two weeks in product design meetings (Figure 4, the two-week coordination cycle) to discuss product architecture and establish clear digital-physical product integration design principles to help coordination.

The project experienced a significantly increased coordination cost. The project manager: "*Compared to other projects, there would have been less need for solving problems and clarifying the direction by now and with most issues resolved, the different subprocesses would be able to just do theirs. But in* [Project D] *everything is so integrated that most decisions affect other project parts, so decisions need to be taken as a team. This requires double the time in* [project management] *meetings …. We have to prioritize our topics very precisely to make sure we get to discuss the most important parts.*" Also, the cadenced review meetings between management and the project management team were set with a much higher frequency. The digital design responsible was added to the project management team to ensure availability of the right experience for project decisions. In general, the project management team members experienced a broadening and an overlapping of their roles to effectively manage the project. Other digital roles included the digital production responsible and four digital technology and experience concept developers. All digital roles within COMP acted as digital-physical translators or liaisons.

Coordination was directly addressed in the project management meetings. This included providing fast feedback to the digital app vendor for their next build loop, thus benefitting from the vendor's agility. Project management also focused on engaging project members who were either experienced with digital-physical product development or motivated to learn to compensate for the high degree of uncertainty.

4.3.4 Project E: Coordination via LeSS and SAFe inspired coordination practices

Project E's 14 subprocesses included a digital-physical product design and a firmware subprocess that both did four-week sprints, an external app vendor who did weekly sprints, three additional software component subprocesses that did two-week sprints and six other subprocesses predominantly adhering to standardized, non-sprinting processes including product packaging and marketing material development. The project decided to test a set of agile coordination practices. From the LeSS framework, which is greatly inspired by Scrum, but aimed at coordinating the work of several development teams, the project adopted the cadenced project review meetings and the daily stand-up meetings. The latter were focused on the collaboration between the external digital app vendor and COMP's physical and digital-physical user experience designers. From SAFe the project adopted PI planning.

Since most of the project members were allocated to other projects for the majority of their time, the coordination practices had to be highly efficient and focused on reducing the cost of coordination. Therefore, the project practiced a four-week coordination cycle across all the subprocesses (see Figure 5). This enabled them to achieve a more complete component integration within each cycle. Each cycle started with a two-hour workshop consisting of a one-hour project review of, for example, a demonstration video of the latest digital app or a prototype demonstration of the latest firmware update, and a one-hour session focused on dependency and risk mapping.

Similar to Project D, the aim was to secure strong project transparency and accommodate mutual adjustment, but the frequency was lower due to scarce time and less uncertainty.

Like in Project D, these coordination practices supported different subprocess practices to co-exist, due to the focus on dependencies coupled with trust in the subprocess teams to do their own planning effectively. Also, different planning methods such as story point estimation (digital) vs. hours per tasks (physical) could co-exist as the dependency mapping was not concerned with measures of duration.

4.3.5 Project E: Supplementing coordination practices

In Project E several project members highlighted a preference towards few standardized meetings coupled with more informal meetings, i.e. mutual adjustment, to spend their time in the most efficient way.

The coordination with the external vendor was formalized in the form of daily video meetings of up to 30 minutes (Figure 5). The Monday meeting would typically relate to the fast feedback provided by COMP on the weekly builds from the app vendor; the Wednesday meeting would involve the full project management team and focus on dependencies, planning and impediments. The meetings included the digital-physical user experience designer and the digital producer from COMP, who would invite additional COMP project members from other subprocesses, typically digital, according to need.

Fast decision making on the digital-physical product design was enabled by clear digital-physical integration principles and by empowering three project members (one physical, one digital and one digital-physical) to make the design decisions. Additional coordination efficiencies were achieved by the physical product and digital-physical user experience designers cooperating as one subprocess. Finally, replacing the physical product design responsible with a digital-physical product designer, prevented the need to add an additional digital-only project management team member.

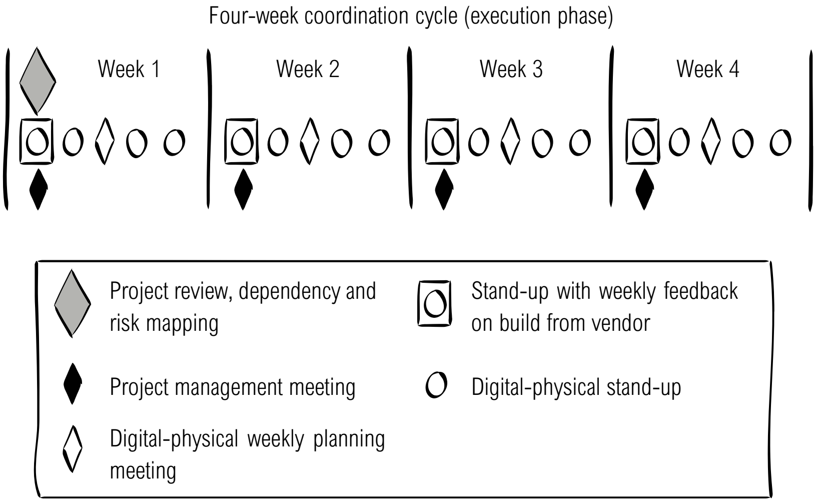

Figure 5 Project E's standardized meta-process of coordinating events

Like in Project D, the project management team experienced more overlapping roles and a need to focus more on coordination practices such as organizing, and securing office space for co-location, IT sharing platforms allowing transparency of e.g. digital epics and features, and promoting further transparency using wall space and white boards for e.g. large sticky note project plans. Finally, Project E's manager had to consider the cost of coordination in terms of the time needed for coordination from busy project members. His digital background enabled him to function as a digital-physical translator and encourage an agile mindset.

4.3.6 Performance consequences

Contrary to the norm in COMP, the project management teams of projects D and E realized the impossibility of engaging with all the detailed planning negotiations themselves as these, due to increased diversity, complexity and uncertainty and the differences between digital and physical development and the differences between digital and physical development including different development cycle lengths, planning practices, language and mindsets, required subprocess expertise and local decision-making. Hence, lateral linkages via empowered, cross-functional mutual adjustment facilitated by the Scrum events and the dependency mapping became key for coordination success in the projects, as the transparency, inspection, feedback and goal clarity enabled careful trade-offs ensuring deliberate suboptimization of the digital development, the physical development, or both. As an example, a series of trade-off decisions pushed Project D's digital vendor into earlier binding: "*... we are forced to really trust our vendor when they say: 'these things are not in the app now, but they will be there later.' ... It has been difficult for* [the digital vendor] *to make certain design choices early, resulting in some choices being open a bit too long for* *what was comfortable for* [COMP]. *Now, the project is converging quickly, and we need to make decisions. We now have to deselect design options as we have run out of time for* [locking the Bill of Materials] *next week.*" Also, to better adhere to the physical dependencies the vendor changed from Scrum to a version of Scrumban: "*They can still do Scrumban, but cannot be truly agile.*"

Discussing the effects of the standardized Process w/ hw versus the agile inspired coordinating meta-process, the manager of Project E stated: "*There is no doubt that implementing these coordination events has been the biggest help.*" Inspired by agility with its focus on process control via transparency, inspection and adaptation coupled with empowered mutual adjustment, the meta-process provided the ability to effectively coordinate the digital and physical subprocesses to optimize for full project performance. The coordination performance consequences from the dependency mapping were considered highly valuable by nine out of ten participants in both projects. One respondent commented: "*These meetings are a great opportunity to get all the relevant stakeholders together in one room to talk about key dependencies. I think they've been invaluable and I would recommend this process going forward.*" Another added: "*Coming out of the meetings it is super clear what needs to happen. In other projects, before, the dependency understanding was informal.*" Finally, the Project D project manager stated: "*If I were to attribute the success of this project to one practice, it would be the dependency mapping*".

Proposition 3: Coordination through standardization of process in the form of a standardized meta-process of cadenced coordination events, combined with empowered and informed individuals, facilitates mutual adjustment, which enables better informed stability-adaptability trade-off decision-making.

Both projects saw the digital-physical development requiring more facilitation of cross-digital-physical process and content learning and more hands-on project management to continuously adjust and fine tune the needed coordination practices. A Project D management team member stated: "*I am no expert to answer this question* [on coordination practices], *as we are still learning every day, and we have not cracked the nut. And every phase is different. Now we are working in a slightly different way than we did when I entered the project. … When I first entered the project, I needed to gain digital knowledge, understand* [the digital design responsible], [the digital production responsible] *and understand how the* [app vendor] *was working. We cannot just divide and conquer; we need to collaborate strongly. So, I needed to be able to understand. … Still, there are many things I do not understand.*"

The cross-functional learning accommodated by the meta-processes became key for coordination success. In Project D's final retrospective meeting, the project team concluded that the biggest performance effects were the feeling of being one digital-physical team working towards a common goal every two weeks, learning from each other in a cross-functional and largely co-located setting, and the increased decision making quality due to the transparency provided by the project reviews.

The dependency mapping helped with cross-functional learning, as stated by a participant: "*... It is great to hear what the other subprocesses need, so we can all support their needs. ... and* [the dependency mappings] *help with cross-functional learning.*"

Not only did the learning inform the coordination, and vice versa, but the ongoing rich-medium coordination also helped surface and reduce equivocality due to conflicting mindsets. Project E's manager was able to address some of these in the dependency workshops, such as challenging non-agile subprocesses to start earlier collaboration with some of the agile subprocesses, by e.g. sharing early assumptions and drafts, instead of waiting until their deliverable had matured in quality. The manager of Project D sometimes reminded non-agile participants to take more risk in their decision making, too.

Proposition 4: Effectively coordinating digital-physical product development involves facilitating ongoing cross-functional learning about processes, content and mindsets, and adapting coordination practices accordingly.

4.3.7 Consolidation

Figure 6 consolidates the four propositions in a refined version of the research model of Figure 3 from a coordination perspective.

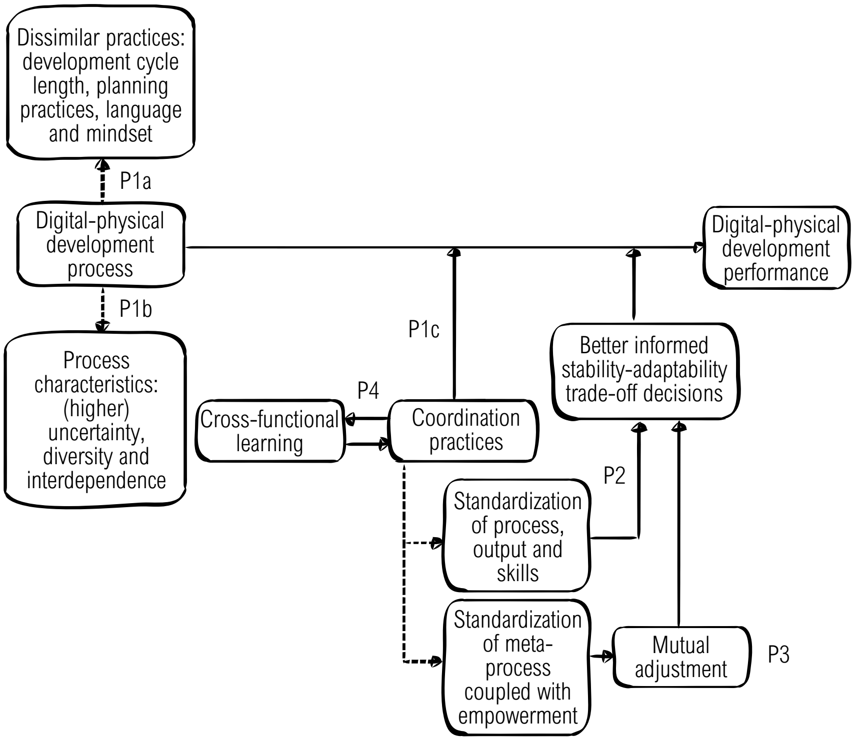

Figure 6 Research model (updated from Figure 3)

5 Discussion: theoretical and managerial implications

This research addresses a gap in the immature digital-physical product development literature (Nambisan et al., 2017; Holmström, 2018) concerning how to coordinate digital-physical product development (Hendler, 2019).

The research demonstrates that the relationship between the *digital-physical development process* and the relatively higher *uncertainty, diversity* and *interdependence* of the combined digital-physical development process and the *performance* of that process is impacted by the *coordination practices*, and shows how specific practices can help to successfully coordinate digital-physical product development. The research inductively illustrates the *coordination practices* in the form of four propositions on the coordination contingencies (Proposition 1) and suitable coordination practices (Propositions 2-4).

More specifically, first, this research contributes with an elaboration on the work by Hendler and Boer (2019) from a coordination perspective. It demonstrates that when combining digital-physical product development the relatively higher degrees of uncertainty, diversity and interdependency, as well as different development cycle lengths (e.g. late versus early binding), planning practices (e.g. stories vs. man-hours), language and mindsets (Proposition 1), challenge a traditional manufacturer's coordination practices.

Second, the research contributes by demonstrating how the specific characteristics of digital-physical product development are successfully coordinated using a mix of Mintzberg's (1979) mechanisms (Proposition 2 and 3). This mix accommodates the needed stability and agility: 1) *mutual adjustment* between subprocesses to enable agility, and 2) *standardization* of process, output and skills to allow some stability, and help balance agility and stability through visualization of process constraints (Galbraith, 1973). This mix of mechanisms can be implemented and supplemented by additional coordination practices across strategy, organizational arrangements and technology (Paashuis and Boer, 1997), e.g. liaison roles and IT sharing platforms.

Third, agile coordination events such as the PI Planning workshop to coordinate teams of teams (Knaster and Leffingwell, 2017), challenge established coordination theory. Relying on informed and empowered staff, these agile coordination events enable cross-functional learning and decentralized mutual adjustment for large groups across digital and physical subprocesses. Thus, agile practices expand Mintzberg's (1979) contingency-based model, which suggests that mutual adjustment is an effective coordination mechanism only for small groups and omits the option of standardizing coordination through cadenced events (Figure 2). As COMP experienced, an increase in project uncertainty with the digital-physical projects meant that these projects could no longer be sufficiently coordinated by standardization: mutual adjustment became necessary. Standardized agile coordination events enable large groups consisting of smaller groups (i.e. the subprocess teams) working on a variety of highly uncertain but interdependent tasks to effectively coordinate via mutual adjustment. Figure 7 is an adaptation of Figure 2, where *standardization of coordination events* is added as an object of standardization, to offer effective coordination for both smaller and larger group sizes under high task complexity and uncertainty. In this way, Mintzberg's continuum of coordination mechanism is expanded to include the agile approach to organization under uncertain and complex circumstances (e.g. Rigby et al., 2016), by increasing the information processing capacity through standardizing cadenced, lateral linkages (Galbraith, 1973) within and between teams (e.g. Daft, 2004). Moreover, several agile events seem to mix some of the integration mechanisms along the continuum proposed by Daft and Lengel (1986) with respect to their relative capacity for uncertainty and equivocality reduction. The PI Planning workshop, for example, offers an efficient means of objective data exchange via the formalized dependency map *as well as* a context to build and share interpretations of problems and their solutions via an open discussion session as a part of the agenda, allowing for rich information exchange with high-frequency feedback.

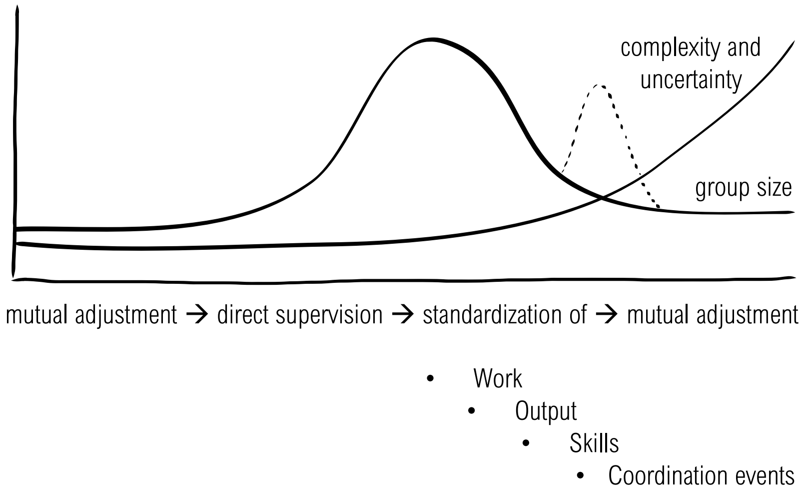

Figure 7 A contingent continuum of coordination mechanisms (adapted from Figure 2).

Fourth, Proposition 4 suggests how process learning and subsequent content and process adaptation are important to coordinate successfully in digital-physical development within a digitalizing manufacturer and how the agile practices designed for team learning also enable differences in mindsets to surface and be addressed. This corresponds with suggestions from inter-firm coordination research, which describe an increased need for coordination to overcome large differences (Prencipe et al., 2003; Lakemond et al., 2006).

Fifth, the coordination examples demonstrated by this research allows the development subprocesses, agile or not, to proceed according to their own subprocess characteristics and preferred practices, that is, to the extent allowed by the ongoing, cross-functional negotiation of trade-offs between stability and agility. This means that differences in sprint cadences, planning methods and method-specific roles can co-exist with only few modifications, such as the digital vendor of Project D changing from Scrum to Scrumban. Late vs. early binding can be renegotiated continuously, leading, for example, the digital vendor of Project D to move more design decisions forward. Accordingly, this set of coordination practices supports the observation that trade-offs between the digital and physical subprocesses are not only necessary (Hendler, 2019) but also achievable. As the COMP example demonstrates, trade-offs can be made deliberately and, hence, kept to a minimum in order to optimize for overall project performance.

Finally, this research contributes to the digital-physical product development literature by offering a specific and successful instantiation of how to combine stability and agility optimized coordination methods, each of which have significant advantages and disadvantages on their own (Karlström and Runeson, 2006; Cordeiro et al., 2007; Eklund and Bosch, 2012; Eklund et al., 2014; Lwakatare et al., 2016; Könnölä et al., 2016; Eklund and Berger, 2017)). In effect, the research demonstrates what could be regarded as an agile-stage-gate process, as suggested by Cooper (2016). However, the gates in COMP's development phase are replaced by a standardized process with integration points of deliverables unaccompanied by a traditional management go/no-go meeting, but by separate, cadenced management reviews. The resulting process model consists of an elaborate deliverables schedule (Proposition 2) where the gates signify key integration points, as well as a meta-process describing cadenced agile coordination events (Proposition 3).

To help managers design successful coordination practices, Table 2 and Figures 4 and 5 present the implementation across process, strategy, organizational arrangements and technology. Table 4 summarizes the coordination challenges and the corresponding, successful coordination practices.

Table 4 A summary of the coordination challenges and successful, tested solutions

#	Digital-physical coordination challenges	Coordination practices
1	**Increased diversity:** The standardized product development process does not describe the digital deliverables and their timing relative to interdependencies, i.e. it does not facilitate coordination of the work that needs to be done via standardization of known output, as is normal for product development in COMP.	Standardize digital development outputs and their latest timing relative to project phases and other interdependencies for difficult projects (large, diverse, interdependent and uncertain projects).
2	**Increased diversity:** High uncertainty regarding digital project roles and responsibilities throughout full product life-cycle	Standardize needed skills, including their roles and their responsibilities.
3	**Increased uncertainty, diversity and interdependency:** Subprocess development work is organized according to local priorities and subprocesses, causing insufficient product component integration, i.e. neglected interdependencies when higher degree of interdependency, diversity and uncertainty.	Standardize cadenced, cross-functional coordination enabling mutual adjustment.
4	**Increased uncertainty:** Significant increase in uncertainty in the first half of the execution phase compared to the large majority of product development projects	More, standardized and cadenced coordination implemented including scrum and dependency mapping. Accepting planning to be subject to ongoing adjustment where feasible.

5	**Increased interdependency:** Specific challenges around coordinating high levels of interdependency between multiples software components such as the need to utilize the same code platform	Heavy up-front coordination as part of sprint events concerning standardization of work and output, such as ensuring good workflows, integration testing and ongoing transparency.
6	**Increased interdependency, early vs. late binding:** Coordinating the orchestration of challenging design decisions when interdependent physical and digital design decisions are required at different points in time, i.e. early and late binding	Standardized, cadenced coordination enabling ongoing mutual adjustment concerning trade-offs, i.e. dependency mapping.
7	**Increased diversity:** Working with external and non-co-located digital vendors in different time zones	More coordination and increased standardization of coordination
8	**Increased diversity:** Internal digital capabilities are scarce and have little time for coordination activities	Effective, standardized, cadenced, larger coordination events, supplemented with ad hoc coordination where needed between subprocesses
9	**Increased diversity:** Limited cross-digital-physical-domain knowledge	Coordinate for effective information sharing, i.e. agile inspired practices. Translator/liaison roles.
10	**Increased diversity:** Digital and physical development represent two different sets of practices that involve two different mindsets that become evident when coordinating	Dialogue by mutual adjustment. Standardize norms by role modelling and discussing these as part of coordination events.
11	**Increased diversity, planning:** Digital and physical development represent two different planning practices. Ongoing prioritization of backlog epics and stories with story points vs. early planning of detailed tasks with estimation of man hours needed	Digital planning adheres to hard physical integration points using e.g. Scrumban. Coordinating liaison roles, cadenced planning meetings and dependency mapping to ensure fit between different plans. Transparency across various IT planning platforms.

6 Conclusion, limitations and future research

6.1 Conclusion

Optimized for stability and agility, respectively, physical and digital development deploy different coordination practices. So, how do we coordinate these two processes in digital-physical product development? This research explores coordination mechanisms and practices as well as their consequences in digital-physical product development for companies traditionally relying on physical product development. Combining an embedded case study approach with action research within a successful global manufacturer of B2C products, a research model was inductively illustrated by four propositions.

Proposition 1 elaborates on Hendler and Boer's (2019) suggestion that digital-physical development is characterized by a different set of contingencies, i.e. process characteristics and differences between digital and physical development including different development cycle lengths (e.g. late versus early binding), planning practices (e.g. stories vs. man-hours), language and mindsets that renders existing horizontal project coordination mechanisms ineffective. Propositions 2 and 3 deploy Mintzberg's (1979) contingency based coordination theory. They demonstrate that effective digital-physical coordination involves *standardization of process, output* and *skills* to accommodate the stability needed for efficient physical product development and take in agile coordination events, such as Scrum and PI planning, to facilitate the *mutual adjustment* needed to allow agility and the differences between digital and physical product development to be continuously and successfully negotiated. Proposition 4 suggests the importance of facilitating cross-functional learning about both process and content, continuously adapting coordination practices accordingly and addressing conflicting mindsets. Finally, this research provides a concrete example for practitioners of how to coordinate digital-physical product development effectively.

6.2 Limitations and future research

Future research should further develop and operationalize the research model depicted in Figure 6, and especially consider coordination practices within a variety of company contexts, e.g. born-digital or born-digital-physical companies, less mature and smaller manufacturers, or involving only co-located digital developers. The coordination practices tested in the research all proved suitable. However, there might be other coordination practices or combinations thereof, that may prove to be equally or more suitable in different contexts. Furthermore, it may be relevant to research digital-physical coordination from a learning perspective to further explore the consequences of making the digital-physical product development process more agile.

Due to the immaturity of this field, more qualitative research, case studies and action research, is needed, first, to discover and test practices that best facilitate digital-physical coordination and, second, to contextualize these findings. Later on, quantitative studies are needed to rigorously test the propositions developed in these studies.

References

Adler, P.S. (1995), ‘Interdepartmental interdependence and coordination: The case of the design/manufacturing interface’, Organization Science, Vol. 6 No. 2, pp. 147-167.

Bialasiewicz, J.T. (2017), ‘Interaction of concurrent processes in cyber-physical systems’, Proceedings of the 14th IEEE International Conference on Industrial Informatics, Polish-Japanese Academy of Information Technology, Warsaw, Poland, pp. 516–521.

Boehm B. and Turner, R. (2004), Balancing agility and discipline: A Guide for the Perplexed, Addison-Wesley, Crawfordsville, IN.

Boehm, B. and Turner, R. (2005), ‘Management challenges to implementing agile processes in traditional development organizations’, IEEE software, Vol. 22 No. 5, pp. 30-39.

Boer, H. and During, W. E. (2001), ‘Innovation. What innovation? A comparison between product, process and organisational innovation’, International Journal of Technology Management, Vol. 22 No. 1-3, pp. 83-107.

Burns, T. and Stalker, G. M. (1961), The Management of Innovation, Tavistock Publications, London.

Caniato, F., Doran, D., Sousa, R. and Boer, H. (2018), ‘Designing and developing OM research – from concept to publication’, International Journal of Operations & Production Management, Vol. 38 No. 9, pp. 1836–1856.

Conforto, E. C., Salum, F., Amaral, D. C., Da Silva, S. L. and De Almeida, L. F. (2014), ‘Can agile project management be adopted by industries other than software development?’, Project Management Journal, Vol. 45 No. 3, pp. 21-34.

Cooper, R. G (1990), ‘Stage gate systems: A new tool for managing new products’, Business Horizons, Vol. 33 No. 3, pp. 44-54.

Cooper, R. G. (2008), ‘Perspective: The stage-gate® idea-to-launch process—update, what's new, and nexgen systems’, Journal of product innovation management, Vol. 25 No. 3, pp. 213-232.

Cooper, R.G. (2016), ‘Agile-stage-gate hybrids: The next stage for product development’, Research Technology Management, Vol. 59 No. 1, pp. 21-29.

Cordeiro, L., Barreto, R., Barcelos, R., Oliveira, M., Lucena, V. and Maciel, P. (2007), ‘Agile development methodology for embedded systems: A platform-based design approach’, in Leaney, J., Rozenblit, J. W. and Peng, J. (Ed.), Proceedings of the 14th

Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems, Tucson, USA, pp. 195-202.

Coghlan, D. and Brannick, T. (2010), Doing Action Research in Your Own Organization, SAGE, London.

Daft, R. L. (1992), Organization Theory and Design, Western Publishing Company, St. Paul, MN.

Daft, R. L. (2004), Organization Theory and Design, Thomson South-Western, Cincinnati, OH.

Daft, R. L. and Lengel, R. H. (1986), 'Organizational information requirements, media richness and structural design', Management Science, Vol. 32 No. 5, pp. 554-571.

Eklund, U. and Berger, C. (2017), 'Scaling agile development in mechatronic organizations. A comparative case study', Proceedings of the 39th IEEE/ACM International Conference on Software Engineering: Software Engineering in Practice Track, Buenos Aires, Argentina, pp. 173-182.

Eklund, U. and Bosch, J. (2012), 'Introducing software ecosystems for mass-produced embedded systems', in Cusumano, M.A., Iyer, B. and Venkatraman, N. (Ed.), Proceedings of the 3rd International Conference of Software Business, Cambridge, USA, pp. 248-254.

Eklund, U., Olsson, H.H. and Strom, N.J. (2014), 'Industrial challenges of scaling agile in mass-produced embedded systems', in Dingsoyr, T. and Moe, N.B., Tonelli, R., Counsell, S., Gencel, C. and Petersen, K. (Ed.), Proceedings of the 15th International Conference on Agile Software Development, Rome, Italy, pp. 30-42.

Galbraith, J.R. (1973), Designing Complex Organizations, Addison-Wesley, Reading, MA.

Hansen, M.T. and Birkinshaw, J. (2007), 'The innovation value chain', Harvard Business Review, Vol. 85 No 6, pp.121-130.

Heeager, L. T., Svejvig, P., and Schlichter, B. R. (2016), 'How agile methods inspire project management – The half double initiative', eProceedings of the 11th International Research Workshop on Information Technology Project Management (IRWITPM), Association for Information Systems, Dublin, pp. 43-55.

Hendler, S. (2019), 'Digital-physical product development: A qualitative analysis', European Journal of Innovation Management, Vol. 22 No. 2, pp. 315-334.

Hendler, S. and Boer, H. (2019), ‘Digital-physical product development: a review and research agenda’, International Journal of Technology Management, Vol. 80 No. 1-2, p. 12-35

Holmström, J. (2018), ‘Recombination in digital innovation: Challenges, opportunities, and the importance of a theoretical framework’, Information and organization, Vol. 28 No. 2, pp. 107-110.

Hong, Y., Pearson, J. N. and Carr, A. S. A. (2009), ‘Typology of coordination strategy in multi-organizational product development’, International Journal of Operations & Production Management, Vol. 29 No. 10, pp. 1000-1024.

Joglekar, N. R. and Rosenthal, S.R. (2003), ‘Coordination of design supply chains for bundling physical and software products’, Journal of Product Innovation Management, Vol. 20 No. 5, pp. 374-390.

Karlsson, C. and Lovén, E. (2005), ‘Managing new technology integration: Integrating software in manufactured products’, International Journal of Innovation Management, Vol. 9 No. 3, pp. 343-370.

Karlström, D. and Runeson, P. (2006), ‘Integrating agile software development into stage-gate managed product development’, Empirical Software Engineering, Vol. 11 No. 2, pp. 203-225.

Knaster, R. and Leffingwell, D. (2017), SAFe Destilled: Applying the Scaled Agile Framework® for Lean Software and Systems Engineering, Addison-Wesley Professional, Boston.

Kniberg, H. and Skarin, M. (2009), Kanban and Scrum: Making the Most of Both. Retrieved from https://www.infoq.com/minibooks/kanban-scrum-minibook

Könnölä, K., Suomi, S., Mäkilä, T., Jokela, T., Rantala, V. and Lehtonen, T. (2016), ‘Agile methods in embedded system development: Multiple-case study of three industrial cases’, Journal of Systems and Software, Vol. 118 No. 8, pp. 134-150.

Kuwashima, K. and Fujimoto, T. (2013), ‘'Performance measurement in product development research: A literature review’, Annals of Business Administrative Science, Vol. 12 No. 4, pp. 213–223.

Lakemond, N., Berggren, C., Van Weele, A. (2006), ‘Coordinating supplier involvement in product development projects: a differentiated coordination typology’, R&D Management, Vol. 36 No. 1, pp. 55-66.

Larman, C. and Vodde, B. (2016), Large-Scale Scrum: More with LeSS, Addison-Wesley Professional, Crawfordsville, IN.

Lenfle, S. and Loch, C. (2010), 'Lost roots: How project management came to emphasize control over flexibility and novelty', California management review, Vol. 53 No. 1, 32-55.

Lewin, K. (1946), 'Action research and minority problems', Journal of Social Issues, No. 2, p. 34-36.

Lwakatare, L. E., Karvonen, T., Sauvola, T., Kuvaja, P., Olsson, H. H., Bosch, J. and Oivo, M. (2016), 'Towards DevOps in the embedded systems domain: Why is it so hard?', in Sprague, R. H. and Bui, T. X. (Ed.), Proceedings of the 49th Annual Hawaii International Conference on System Sciences, Oulu, Finland, pp. 5437-5446.

Maleki, E., Belkadi, F. and Bernard, A. (2017), 'Systems engineering as a foundation for PSS development project: Motivations and perspectives' in McAloone, T.C., Tseng, M. M., Mortensen, N. H., Shimomura, Y. and Pigosso, D. C. A. (Eds.); Proceedings of the 50th CIRP Conference on Manufacturing Systems 2017, Nantes, France, pp. 205–210.

Martini, A., Pareto, L. and Bosch, J. (2016), 'A multiple case study on the inter-group interaction speed in large, embedded software companies employing agile', Journal of Software-Evolution and Process, Vol. 28 No. 1, pp. 4-26.

Mintzberg, H. (1979), The Structuring of Organizations, Prentice-Hall, Englewood Cliffs, N.J.

Mocker, M. and Fonstad, N.O. (2018), 'Driving digitization at Audi', Proceedings of ICIS 2017: Transforming Society with Digital Innovation, Association for Information Systems, pp. 1–15.

Nambisan, S, Lyytinen, K, Majchrzak, A, and Song, M. (2017), 'Digital innovation management: Reinventing innovation management research in a digital world', MIS Quarterly, Vol. 41 No. 1, pp. 223-238.

Nambisan, S. and Wilemon, D. (2000), 'Software development and new product development: potentials for cross-domain knowledge sharing', IEEE Transactions on Engineering Management, Vol. 47 No. 22, pp. 211-220.

Paashuis, V. and Boer, H. (1997) 'Organizing for concurrent engineering: An integration mechanism framework', Integrated Manufacturing Systems, Vol. 8 No. 2, pp. 79-89.

Perrow, C. (1967), ‘A framework for the comparative analysis of organizations’, American Sociological Review, Vol. 32 No. 2, pp. 194-208.

Porter, M.E. and Heppelmann, J. E. (2015), ‘How smart, connected products are transforming companies’, Harvard Business Review, Vol. 93 No. 10, pp. 96-114.

Prencipe, A., Davies, A. and Hobday, M. (2003), The Business of Systems Integration, Oxford University Press, New York, N.Y.

Rigby, D. K., Sutherland, J. and Takeuchi, H. (2016), ‘Embracing agile: How to master the process that is transforming management’, Harvard business Review, Vol. 94 No. 5, pp. 40-50.

Rottier, P. A. and Rodrigues, V. (2008), ‘Agile development in a medical device company’, in Melnik, M., Kruchten, G. and Poppendieck, P. (Ed.), Proceedings of the Agile 2008 Conference, Toronto, Canada, pp. 218-223.

Schwaber, K. and Sutherland, J. (2017), ‘The Scrum Guide™, available at: https://www.scrumguides.org/docs/scrumguide/v2017/2017-Scrum-Guide-US.pdf#zoom=100 (accessed 20 November 2018)

Sutherland, J. (2015), Scrum: The Art of Doing Twice the Work in Half the Time, RH Business Books, London.

Svahn, F. (2012), Digital Product Innovation: Building Generative Capability through Architectural Frames, PhD thesis, Umeå University, Umeå, Sweden.

Svahn, F. and Henfridsson, O. (2012), ‘The dual regimes of digital innovation management’, Proceedings of the Annual Hawaii International Conference on System Sciences, Maui, USA, pp. 3347-3356.

Svahn, F., Lindgren, R. and Mathiassen, L. (2015), ‘Applying options thinking to shape generativity in digital innovation: An action research into connected cars’, Proceedings of the Annual Hawaii International Conference on System Sciences. IEEE Computer Society, pp. 4141–4150.

Swink, M. (1999), ‘Threats to new product manufacturability and the effects of development team integration processes’, Journal of Operations Management, Vol. 17 No. 6, pp. 691-709.

Thompson, J.D. (1967), Organizations in Action. Social Science Bases of Administrative Theory, McGraw-Hill, New York.

Turner, R. (2007), ‘Toward Agile systems engineering processes’, Crosstalk. The Journal of Defense Software Engineering, 2007 (April), pp. 11-15.

Vandevelde, A. and Van Dierdonck, R. (2003), ‘Managing the design-manufacturing interface’, International Journal of Operations & Production Management, Vol. 23 No. 11, pp. 1326-1348.

Wolfenstetter, T., Böhm, M., Krcmar, H. and Bründl, S. (2016), ‘Why product service systems development is special’, in Framinan, J. M., Gonzalez, P. and Artiba, A. (Eds.), Proceedings of the International Conference on Industrial Engineering and Systems Management, IEEE IESM 2015, Institute of Electrical and Electronics Engineers Inc., Seville, Spain, 21–23 October, pp. 1221–1228.

Yoo, Y. (2010), ‘Computing in everyday life: A call for research on experiential computing’, MIS Quarterly, Vol. 34 No. 2, pp. 213-231.

Appendix D. Action research diary structure

Below the template that was used for the daily entries of the action diary is showed. The template included comments and questions to help reflection. The template for the action research diary is inspired by Kolb's learning cycle as presented by Coghlan and Brannick (2010).

Loop name and date:

Concrete experience: What was diagnosed/learned of new information? What was planned and by whom? What happened? What was the outcome?

Reflection:

Content: Did the initial diagnosis fit? What have I learned about the specific issue?

Process: Does the action research process work? Does the implementation work? Does the team learning process work?

Premise: Have the assumptions changed? Do we see the issue in a different light now? Group think? New perspective? What-I-think-I-know?

Conceptualization: Relate relevant concepts and form tentative conclusions, generalizations and propositions.

Action implications: How to apply new learning?

Appendix E. Recommendation creation workshop

Day 1

Time	Agenda
8:30 – 9:20	**What:** Introduction **How:** • Stage setting & re-cap to ensure shared understanding of problem. • Introduce workshop scrum board and iterative workshop approach. • Exercise: experience circle: your experience with digital-physical. • Energizer. • Workstream purpose, framework and focus (way of working principles, real project examples). • Re-cap current process flow and key milestones for hw, fw, sw, app, physical product development and live phase based on the actual plan of Project X.
9:20 – 10:25	**What:** Build future-state execution phase and live phase process and test against [Project X's] and [Y's context and experience]. **How:** Divide in groups per phase and run short sprints with reviews between the groups: • Define to-be – the realistic dream! Team work in sprints: ○ Sprint 1 + review.
Break – 5 min	
10:30 – 12:00	○ Sprint 2 + review. ○ Sprint 3 + review. Review goal: Review and align on major milestones, subprocesses, phases, tasks, dependencies, key integration points and add/change tasks as needed. Ensure responsibles are added to each task.
LUNCH – 30 min	

12:30 – 13:00	**What:** Prioritise workshop effort and ensure clear accountability of process outcome.
	How:
	• Plenum: Review in silent brainstorm and add large voting dots for important process areas to close the capability gap going forward, i.e. important for success and explain briefly for each highlighted area.
	• Plenum:
	  ○ Define overall accountability of the digital-physical project output.
	  ○ Add next to each output description sticky notes: Who is accountable for which components, platform establishment, coherence?

13:00 – 14:50	**What:** Based on the to-be processes: Define titles/competencies needed *to ensure we have strong argumentation for new roles needed per project as well as early role descriptions for new/changed roles.* **How:** • Plenum: List needed titles/competences/roles across both phases. • In groups per process: o Add phase specific role description on sticky notes for new titles – one-liners. o Mark where the new titles play a role by adding mini sticky notes with title abbreviations on relevant tasks in flow chart. o Estimate needed FTR per new role in the given phase for a Project X type project by writing next to role name per phase. • Plenum: o Review new/changed roles per phase. Align across phases. o Add large dots next to the most important titles for closing the capability gap.
BREAK – 10 min	
15:00 – 17:20	**What:** Define project collaboration structure and governance structure **How:** • Plenum: Define *key* decisions per phase (non-portfolio) on white board via brainstorm, write on A5 stickies. • Group the decisions based on which can be done by the project team and which cannot. o Group the latter further into who can make them – first draft. o Present sprint exercise: new groups, new team backlog, produce posters. Divide group into 3 teams and run 4 short sprints with reviews: Team 1: Concept for project collaboration organization in execution phase e.g. coordination/planning mechanisms such as cadences, tools needed, principles etc. Team 2: Governance bodies. Team 3: LIVE phase project and governance structure.
BREAK – 10 min	
17:30 – 17:45	**What:** Prioritise to ensure focus **How:** Plenum: Silent brain storm: what do we see as important in closing the capability gap going forward. Mark with large dots. Share highlights in plenum.
17:45 – 18:00	Summary of the day: • Agenda review. • Confidence vote. • Reflections from the day.

Day 2

Time	Agenda
8:30 – 8:45	Re-cap, agenda and reflections.
8:45 – 10:50	**What:** Quality check to-be process against known digital-physical projects. **How:** Divide in process phase groups: Review to-be execution phase and live phase against [Project X and Y]. Run 2 sprints + reviews.
BREAK – 10 min	
11:00 – 12:00	**What:** Mature and document recommendations. **How:** Plenum: Step back and reflect in silent brainstorm: • What are the key elements of our recommendation so far that we want to highlight to management: Place small pink sticky notes – two per person. • Start documentation – via poster summaries. Make motivation based teams. Consider how to scale to full portfolio and if we have applied our guiding principles. o Poster team 1: Document the recommendation part 1 – key elements. o Poster team 2: Document the recommendation part 2 – key elements. o Poster team 3: Define high level 2-year roadmap 2018-2019. Define high level business case (FTR, cost, etc.)?
LUNCH - 30 min	
12:30 – 13:45	**What:** Collect input from management review of recommendations **How:** Welcome • Presentation: Each team present + discussion/feedback. • Capture input per presentation.
13: 45 – 14:10	**What:** Review how much we have covered of the problems at hand **How:** Silent brainstorm + share. What problems are we solving/not solving?
BREAK – 7 min	
14:20 – 15:00	**What**: Make recommendation for more problems **How:** • In plenum: Select topics for further discussion from scrum board and prioritise. • Per topic: Silent brainstorm in groups: concerns and suggestions. Discuss solutions and capture on sticky notes.

15:00 – 15:30	**What:** Final review + plan next step **How:** In plenum • Actions towards management meeting in three weeks. • Review what we have done! • Reflection/feedback. • Energizer.

Appendix F. Overview of the 2nd order data categories supporting Hendler (2019)

85 order categories

Project A

Combination practices

B1 More problem solving and changes in COMP's process due to low uncertainty vs. high uncertainty (e.g. low uncertainty information from digital into physical planning).
B2 Late binding vs. early binding with digital compromising the most.
B3 Physical developers assumes no 'cost of change' when digital materiality. Digital adapts. Mutual learning needed.
B4 Different language/knowledge/norms.
B5 Different cycle lengths mitigated via information flows.
B6 Physical presented many known design constraints early with digital adapting to these while discovering their own.
B7 Big physical front end effort with lack of skills to give clear brief to digital vendor. More co-creation.

Contextual practices

B8 Need to facilitate collaboration and learning between all collaboration partners along the full value chain and with different power balances.
B9 Scarce digital capabilities in advisory board, project leadership, marketing, tech scouting, designers, platform management and market research.
B10 Handover breaks learning curve after front end work.
B11 Processes not designed for full life cycle learning and lack of digital platform support.
B12 Difficult to get digital people allocated to project.
B13 New tech tools needed.
B14 Physical driven front end work but with more focus on earlier proof of technology.
B15 Current business model leaves little room for exploiting digital value.
B16 New market and product requires new marketing.

B17 How to ensure right digital-physical product quality? Old measures insufficient..
B18 New project organization needed with digital people and faster decision-making.
B19 New consumer services training and policies.
B20 Lack of focus on post launch phase.
B21 Wrong testing methods with narrow focus. Too little testing.
B22 Not right legal competences available.

Product development practices

B23 Need to accommodate higher uncertainty and complexity.
B24 More jobs to be done across digital, physical and their integration.
B25 Higher process complexity due to many more moving parts and design parameters.
B26 Higher coordination costs.

Project B

Combination practices

B1 Digital vendor adapted to early physical binding by becoming more agile.
B2 Late binding vs. early binding resulted in much deviation from COMP's processes, much problem solving time and relying on digital adaptability to fix product problems and adapt.
B3 Learning about different assumptions, especially high cost of change vs. low cost of change.
B4 Increased focus on collaboration and trust to remedy different language/knowledge/norms e.g. schedule adherence.
B5 Different cycle lengths required COMP to work in shorter cadenced loops.
B6 Many physical design constraints with digital adapting to the resulting smaller solution space.
B7 Big physical front end effort vs. small digital front end effort due to normally clear digital brief. Focus on early collaboration.

Contextual practices

B8 How to co-create with partner, different power balance.
B9 Scarce dig. competences in COMP for management, contracting and design.
B10 Handover processes breaks learning curve.

B11 COMP's processes/systems designed for exploitation and known output. Not able to handle new dependencies or materiality.
B12 Resource allocation of digital resources not integrated in processes.
B13 Not right tech tools available (self-referential).
B14 Physical driven front end work.
B15 Ill-fitting business model. How to make good business case?
B16 How to communicate? Marketing innovation needed.
B17 No definition of digital quality.
B18 New organisation, project organization, ownership structures and governance needed.
B19 New consumer services policies needed.
B20 Many more tasks to be executed in the same time.
B21 Post launch set-up missing.
B22 New testing methods needed.

Product development practices

B23 Higher uncertainty and digital materiality requires new development practices.
B24 More radical product development required more learning loops (exaggerated by digital).
B25 Higher process complexity.

Project C

Combination practices

C1 Physical cannot easily cope with stuff that was not planned for. Stability/predictability based vs. learn and react (exaggerated by late sw start-up). Maximize and expand physical process system flexibility.
C2 Early vs. late binding (greatly exaggerated by SW starting up late) with digital vendor pressured to fit early binding.
C3 Low need for front-end capabilities in SW development results in SW resource gap when co-creating early. Hired new people.
C4 Different underlying assumptions, e.g. earlier commitments over value in physical vs. value over commitments in SW. More problem solving time.
C5 Physical works with many known design constraints immediately, digital does not, they start with unconstrained brainstorm. Large digital solution space. More time to solve problems and collaborate.
C6 More effort needed due to different work languages. Hard to understand each other's design constraints/worlds.

C7 Adapting to different cycle lengths by supplying information to each other's needs.

Contextual practices

C8 Different digital-physical partner/ collaboration contract type needed due to high project uncertainty. New legal and procurement skills.
C9 Scarce digital design resources in COMP.
C10 The digital designers in COMP does not have the relevant experience for digital-physical product development.
C11 Steep and speedy learning curve requires continuous learning curve.
C12 No room to explore and learn during COMP's project execution phase.
C13 COMPS process does not result in a digital-physical product.
C14 Difficult to get available digital people allocated to your projects.
C15 Uncertain resource needs for project makes it hard to ensure that the project has what it needs with yearly allocation cycles.
C16 No design guidelines or collaboration mechanisms exist across digital and physical to ensure consistency in final product.
C17 Partnership skills lacking for co-creation with external digital partner.
C18 Lack of digital authoring and collaboration tools.
C19 New core product development skills are developed and growing external to COMP.
C20 Digital vendor needs many and early assets from COMP.
C21 Poor contract negotiation skills.
C22 Need for effective collaboration that gives vendor time to explore.
C23 No post-launch operations set-up.
C24 Early focus on the physical product and late focus on digital tech maturation from COMP.
C25 Poorly fitting business model.
C26 Marketing innovation needed.
C27 Little experience with digital eco-system with dependencies to 3rd party devices and software.
C28 What is the right digital and digital-physical product quality?
C29 New project organization and roles including digital roles.
C30 Much more testing needed to reduce risk.
C31 New return policies needed.

Product development practices

C32 Higher uncertainty and complexity.
C33 Building a new process during the project.
C34 Focus on faster team learning.

Appendix G. Cross-project categories supporting Hendler (2019) and their references to the evidence in Appendix F

22 2nd order aggregate categories	**Category reference number (See Appendix F)**
1. Exception management overload in physical	A1, A4, A12, A20, A30, A32, A33, B2, B5, B12, B17, B20, B21, B23, B24, B25, C1, C5, C7, C18, C19, C23
2. Digital-physical co-creation towards early physical binding	A3, A5, A7, A34, B7, B10, B14, C7, C14
3. Early binding is limiting software learning	A2, A3, A7, A8, A12, A20, A22, B1, B2, B6, C1, C2, C6
4. Ensure learning about shared language and process constraints	A5, A6, A9, A11, A34, B3, B4, B6, B8, B10, B11, C3, C4, C8, C10
5. Benefit for physical when enabling digital adaptability	A2, A20, A22, B1, B2, B5, B6, B23, C2, C3, C5, C6
6 .Digital-physical is characterized by higher levels of interdependency, diversity, complexity, uncertainty and larger project size in terms of jobs	A1, A7, A8, A11, A13, A15, A16, A24, A27, A29, A32-34, B2-5, B7, B11, B14, B18, B20, B23-25, C1-7, C11, C18, C23-25
7 .Digital-physical involves post launch product operations	A1, A9, A13, A23, B21, B23, C11, C20, C23
8. Digital-physical requires business model innovation	A9, A13, A25, B15, C15, C20
9. Digital-physical requires a rethink of marketing strategy and communication	A13, A26, B16, B18, B23, B24, C16, C20, C23

10. Digital-physical requires more external orientation	A8, A17, B8, B18, B23, C7, C8, C18, C22, C23, C26
11. Digital-products introduce digital bugs and minimum viable digital product quality that challenge the perception of quality of the physical brand	A4, A28, B17, B19, B22, C9, C17, C19
12. Digital agility can help mitigate physical development uncertainty	A1, A2, B1, B2, B5, B6, B23, C2, C3, C5, C6
13. Better performance by making physical more agile	A1, A4, A7, A22, A30, A32, B5, B23-25, C2, C21, C23, C25, C26
14. Project decisions often involve a trade-off between physical and digital.	A2, A4, A7, A24, B2-4, C1-3, C5, C6
15. Digital-physical can benefit from physical development having later binding	A1, A2, A4, A5, A24, B2, B5, B14, C2, C5, C23, C25
16. Strong collaboration skills	A4, A5, A6, A7, A8, A11, A16, A34, B2-4, B6, B7, B8, B11, B23-25, C1-7, C8, C23, C25, C26
17. The large physical front end effort compared to the relatively small digital front end effort will result in digital resources being scarce when much co-creation is needed.	A3, A5, A7, A9, A24, B7, B14, C7, C14
18. Investment in digital tools needed due to the self-referential nature of digital technology	A3, A18, B13, C13
19. Digital-physical requires new testing and verification techniques	A10, A18, A19, A28, A30, B22, C2
20. Digital platform management is essential, but difficult to integrate into slow moving physical platform management	B9, B11, C9, C11
21. Lacking digital insight on project governance and advisory board level in manufacturer	A14, A19, B9, C9

22. Digital competences needs to permeate the manufacturer's organization	A3, A4, A8, A9, A10, A11, A14, A15, A17, A19, A21, A25, A26, A27, A28, A29, A31, B2-4, B6, B9, B18, C1-4, C6-9, C18

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