Facing extreme uncertainty – how the onset of the COVID-19 pandemic influenced product development

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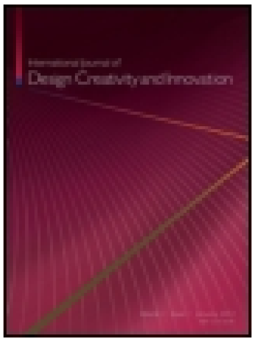

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RESEARCH ARTICLE

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Facing extreme uncertainty – how the onset of the COVID-19 pandemic influenced product development

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ABSTRACT
The COVID-19 pandemic has been a global disruption, but little is known about how it impacted product development. Based on interviews of 24 practicing product development leaders, we find that COVID-19 generated a unique combination of external and internal uncertainties and thus had several direct impacts on product development. Initial adaptations were reported in the level of innovation pursued, the development processes and the resourcing. In terms of level of innovation and resourcing, no uniformity in adaptations were observed: opposite changes were made across radical/incremental, expanding/reducing, local/international and internal/external collaboration balances in the different companies' product development activities. Process adaptations were more uniform in direction, focusing on increasing flexibility and agility. In terms of product development methods for different phases, we find companies quickly seeking creative approaches to replace their traditional methods in idea generation, prototyping, customer interaction, validation etc. with virtual means. Furthermore, changes in human interaction quality, particularly informal interaction, were seen to have far-reaching, unintended negative consequences on their creative efforts, whether in product development, development process or resourcing. Overall, the results highlight the diversity of adaptive choices available to respond to external uncertainties, though more research is still needed on how these influence longer term resilience.

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Product development; uncertainty; COVID-19 pandemic; resilience

1. Introduction

Product development is inherently a creative process that aims to produce an innovative outcome, and this process is marked by uncertainty (Chalupnik et al., 2013; Dong, 2015; Luo, 2015). Uncertainty arises both externally and internally (De Weck et al., 2007) and from the context (Kreye et al., 2011) of product development. Externally, product development is marked by market and technological uncertainty, as well as other exogenous uncertainties such as political and cultural context. Internally, uncertainties emerge related to the organization itself or the product they are developing (De Weck et al., 2007) – the product development organization, managing the people,

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process and resources involved (Chalupnik et al., 2013). Indeed, in many ways, product development, innovation management and design as fields revolve around navigating these uncertainties through different types of practices and methods.

The COVID-19 pandemic, however, has proven not to be a typical case of uncertainty. It manifested in both internal and external uncertainties in disrupting markets, impacting supply chains as well as preventing typical face-to-face work, to name a few facets (Kuckertz, 2021; Sharma et al., 2022). As it permeated all aspects simultaneously, the consequences of uncertainty were particularly hard to predict or control. Traditional risk or uncertainty management methods have been shown to be inadequate for such rare events (Montomoli & Massini, 2013; Murphy & Conner, 2012; Nafday, 2011) – rather, organizational operations are comprehensively shaped by the unfolding crisis. While these studies have considered organizations and their operations, less is known about the effects the crisis has had on product development specifically, and how research and development organizations have responded to these effects.

External crises can paralyze, but they can also be sources of opportunity (Björklund et al., 2020; Davidsson et al., 2020). While studies examining internal crises in complex systems often focus on early detection to avoid failure (e.g. Hajikazemi et al., 2016), studies examining external crises have focused on how organizations can survive, recover from and even thrive in adverse conditions (Grube & Storr, 2018; Monllor & Murphy, 2017; Williams & Shepherd, 2016). For example, Sheffi and Rice (2005) discuss the impact of the September 11th, 2001 terrorist attacks on supply chains and how resilience (ability to recover from difficulties) and flexibility are the key to recovering from an unexpected adverse event. Indeed, to withstand crises, organizations must be resilient, and studies have shown creative innovation and flexible development activities can play a key role in recovery and building resilience. For example, during and in the aftermath of the Financial Crisis, organizations with strong involvement in innovation activities prior to the crisis as well as recently founded fast-growing ventures coped best (Archibugi et al., 2013). Similarly, investing in developing new products (Colombo et al., 2016) or proactive marketing (Srinivasan et al., 2005) during a crisis leads to superior performance both during the crisis and after it. Reviewing emerging research on the COVID-19 pandemic in the context of entrepreneurship, Kuckertz and Brändle (2022) found studies documenting both increases and decreases in innovation activity. Examining COVID-19 related innovations, Ebersberger and Kuckertz (2021) found startups responding faster than larger or public organizations. However, studies on larger organizations' overall efforts in product development remain scarce.

Indeed, despite the benefits of investing in product development and innovation activities during a crisis, surviving through a business decline through actions like cutting costs and risks may be more attractive than proceeding with proactive innovation activities (Hansen & Nybakk, 2018). Furthermore, managers may be less willing to take the risk of innovation when decline is seen as caused by uncontrollable forces (McKinley et al., 2014) such as a pandemic. Indeed, while many have recommended a resilience-based approach for product development, these continue to be rare (Nafday, 2011; Shafqat et al., 2019) as companies lack the financial resources or governance structure to invest in times of crisis.

Given the unprecedented combination of different types of uncertainties, it is unclear how product development has been impacted by the onset of the COVID-19 pandemic and how have companies adjusted their product development in response. In this paper we investigate how the COVID-19 pandemic impacted what the companies develop (level of innovation), how they develop it (processes) and who is involved in the development (resources).

2. Literature review: pathways for resilience in the face of uncertainty

Examining the effects of the uncertainty, product development can be conceptualized as a system whose output is a new product and its market performance. This system is impacted by several uncertainties, COVID-19 being the unique combination of multiple internal and external

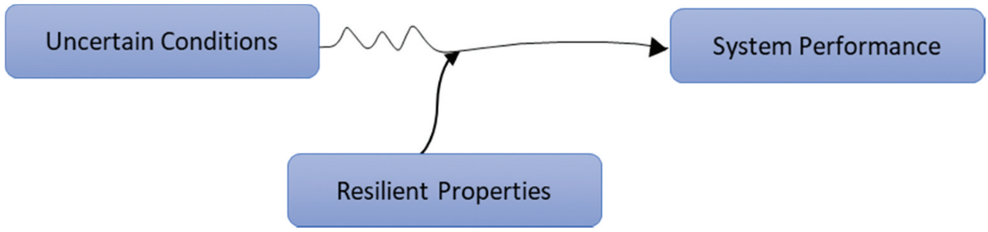

Figure 1. *Conceptual model of system resilience adapted from* Wied et al. (2020).

uncertainties occurring at once. Systems try to dissipate the impact of uncertainties through resilient properties such as deliberate margins built into the system, or active reactions to the uncertainty. Wied et al. (2020) conceptualize system resilience as shown in Figure 1. They propose system performance determined by a set of uncertainty conditions which can be mitigated by a set of resilient properties. In this review, we expand this model and discuss product development performance under various uncertainties and possible resilient properties identified.

The basic premise is that through adjusting properties of the system, adverse effects of uncertain conditions can be mitigated, and positive effects leveraged to increase system performance. In the case of product development, system performance is the operational outcome of a product development organization. This can be the product itself or competitive advantage (Dong, 2015), or more specifically product quality, unit cost, or time to market, which in turn impact product market outcomes (Tatikonda & Montoya-Weiss, 2001).

Past studies have categorized different types of risks and uncertainty that can affect system performance (Jalonen, 2012; Da Silva Etges & Cortimiglia, 2019). While risk can be considered in terms of events with occurrence probabilities, uncertainty is rather characterized as an unknown unknown (Teece et al., 2016), which prevents occurrence estimation. Unlike risks that are framed as negative situations to be avoided, some types of uncertainty can be desirable in the context of product development. For example, Calantone et al. (2010) found that technological uncertainty can promote innovation, which in turn can be good for company performance. Also, perceived market risk has been shown to have a positive impact on innovation (Roper & Tapinos, 2016), although Calantone et al. (2010) did not find that in their study. As such, the goal in resilient systems is not to eliminate uncertainty, but to navigate it successfully.

In the context of product development, external market uncertainty and internal technological uncertainty are commonly discussed types of uncertainty (Calantone et al., 2010; Russell & Russell, 1992; Tatikonda & Montoya-Weiss, 2001; Verworn et al., 2008; De Weck et al., 2007). In addition, other external uncertainty categories have also been identified, including regulatory, societal, and economic uncertainty (Jalonen, 2012; Da Silva Etges & Cortimiglia, 2019), as well as internal uncertainties such as lack of modeling unintended interactions, task uncertainty, decision making uncertainty and organizational perceived uncertainty (Bstieler, 2005; Roper & Tapinos, 2016; De Weck et al., 2007). External events such as the global COVID-19 pandemic cannot be reduced to a single category or type of uncertainty, rather, the widespread effects introduced uncertainty into most all these categories through multiple, yet unpredictable, domains.

Faced with uncertainty, resilience is recommended as a proactive approach to uncertainty by many authors (Chalupnik et al., 2013; Hamel & Välikangas, 2003; Nafday, 2011; Shafqat et al., 2019; Sheffi & Rice, 2005). In effect, internal operations can mitigate and leverage external uncertainties, with resilience defined as an ability to rebound from an adverse event and return to equilibrium (Uday & Marais, 2015; Wied et al., 2020; Woods, 2015). Hamel and Välikangas (2003) argue that companies must move from reactive to more forward-thinking approach to achieve resilience. Oehmen and Seering (2011) identified several different means to achieve resilience in product development, including reducing uncertainties systematically, setting schedule, performance, capacity, and other buffers and being agile. Reviewing the literature, we identified three perspectives through which the system of product development can be adapted in face of uncertainty: (a) changing what is done, (b) how it is done and (c) who one does product development with. We will discuss each of these next.

2.1. What – Change the level of innovation

Radical innovation involves difficult design activity to create solutions that are new to the world or company, whereas adjacent innovation is bringing current technology to new markets, and incremental innovation is to consider small derivative design changes. The balance of radical and incremental projects is one reported way to address development uncertainty, but uncertainty also impacts the radical-incremental balance. Studies support both proactively and reactively, balancing the level of innovation in projects to prepare or react to uncertainty. Chao and Kavadias (2008) discuss strategic 'buckets' as a means to balance radical and incremental innovation. According to them, external or market complexity shifts the balance toward radical innovation, while instability shifts the balance toward incremental innovation. In unstable, complex markets, both strategies are needed. The radical-incremental balance can also be impacted by funding. Variable funding moves the balance toward incremental innovation, whereas fixed funding encourages more radical projects (Chao et al., 2009). Technological uncertainty can lead to longer time to market (M. Tatikonda & Rosenthal, 2000), which can also shift the focus toward more incremental innovation. On the other hand, supporting innovation champions, planning entrepreneurial projects, and aggressively looking for new opportunities are also discussed as means to achieve resilience (Demmer et al., 2011). Reducing both market and technological uncertainty is good for product development success for both radical and incremental projects (Verworn et al., 2008). Besides technical and market uncertainty, long term profitability, portfolio fit, and social dimensions can also impact the share of radical and incremental projects (Behrens, 2016).

Besides the radical-incremental balance, Morgan et al. (2020) discuss pivoting, or changing business direction, as a way for small and medium-size enterprises (SME) to respond to exogenous shocks. They discuss mostly two forms of response from past literature: arbitrage and innovation. They argue that existing firms are better off targeting innovation as an approach, since pivoting requires some agility, which might be harder for more established firms (Teece et al., 2016).

2.2. How – Change the process

Montagna and Cantamessa (2019) recommend using different product development processes depending on where the relevant technology is on the technology development S-curve. On the linear portion, optimization and incremental development are working strategies, but not at the ends of the S-curve. Unger and Eppinger (2011) compare traditional stage gate processes with more agile processes and recommend that different types of product development projects require different product development processes, including hybrid processes that are neither stage gate nor more agile spiral processes. Overall, it is not clear what process is best when, and Unger and Eppinger (2011) find that managers may not make an informed choice on which process to choose, but rather follow trends and e.g. peers.

Agile processes have received increasing attention, first in software development, but lately also in hardware, mechatronic and complex system development (Albers et al., 2019; Atzberger & Paetzold, 2019; Hölttä-Otto et al., 2008). Teece et al. (2016) find that the net benefits of organizational agility increase with the degree of uncertainty in the competitive environment. Karimi and Walter (2015) discuss the case of digital disruption in the newspaper industry and how dynamic capabilities were useful, including adapting processes. Also, Oehmen and Seering (2011) mention agile processes as means to achieve resilience. Demmer et al. (2011) support this by suggesting that a more organic organization structure might be beneficial for resilience.

2.3. *Who – Change resourcing*

Adapting both financial and human resources can also help cope with a disruption (Karimi & Walter, 2015). This can mean being frugal and carefully conserving resources (Giones et al., 2020), or directing them toward future programs. The latter may face a political challenge inside a company since the future programs may not appear profitable at the moment (Hamel & Välikangas, 2003).

Collaboration as well as building internal competencies are other strategies recommended for resilience. In a longitudinal study of radical innovation projects at manufacturing firms (IBM, GM, Air Products, DuPont, and Analog Devices), McDermott (1999) found that firms had consistent ways in both building on competencies and using alliances. Building internal technological and market competencies reduces the uncertainty and risk in those areas. Alliances, on the other hand, expand capabilities and share the risk. Demmer et al. (2011) further discuss how both strengthening internal knowledge networks and building external knowledge networks can help with resilience. These tactics can also work in SMEs by externalizing innovation with alliances or by outsourcing as well as inverting internally to foster innovation (Demmer et al., 2011). In the supply chain literature (Habermann et al., 2015; Kwak et al., 2018), the use of local and distributed supply chains is mentioned which is analogous to using internal and external competencies in product development.

The organization culture and values as well as the business environment can impact if and how people decide to change their processes, resources, or the products they are developing (Karimi & Walter, 2015; Russell & Russell, 1992). These could be considered uncontrollable factors in the system resilience model. The above findings from the literature and an elaborated model for adapting to uncertainties in product development are summarized in Figure 2.

The question remains, how are product development firms and product development functions within companies dealing with COVID-19 and the disruption it continues to cause. In this

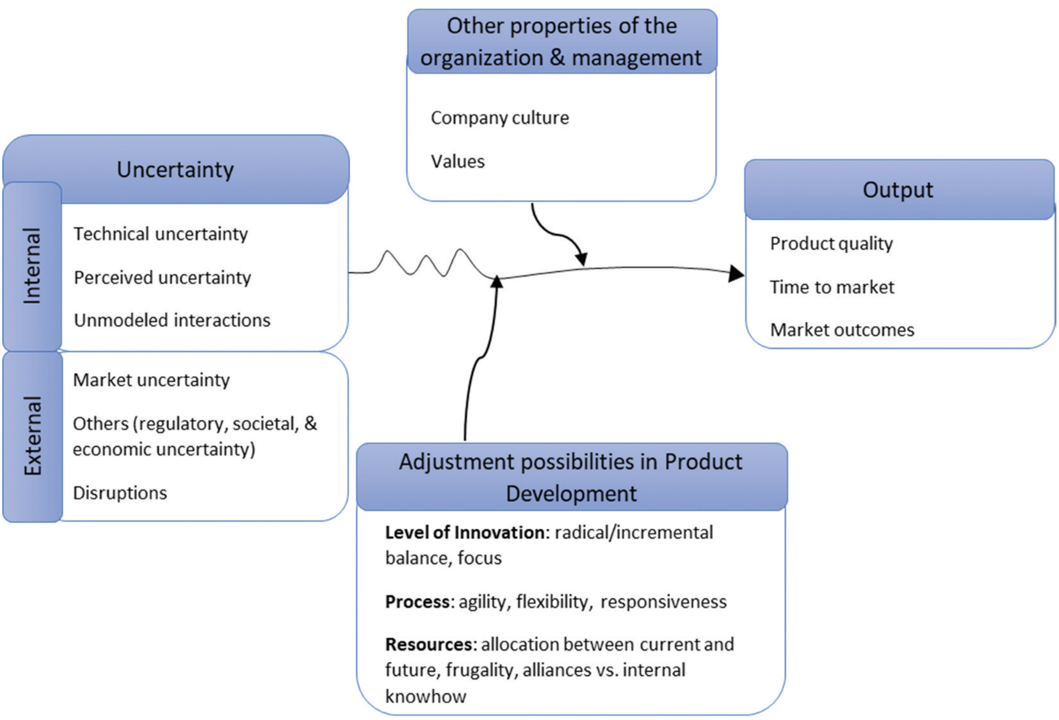

Figure 2. Product development organizational actions in response to uncertainty to achieve performance outcomes.

qualitative study of 23 companies, we investigate both how firms reacted in the immediate and how organizations plan to adapt in the long term.

3. Methodology

This work arose from a workshop study held in September 2020 by the Industrial Relations Committee of the Design Society, an international society of academic and industry members with research interests in design. The Industry Relations Committee fosters academic-industrial collaborations, and this workshop brought together practicing product development experts from Europe and North America to discuss the impact of the COVID-19 pandemic on product development and offered experiences at their respective companies and projects. This panel interview baseline was then expanded with individual semi-structured interviews from additional subjects from different organizations. In this study, expert interviews were used as a qualitative research instrument. For this purpose, a few guiding questions were defined to identify changing work practices and assess the subjective experience of the participants in their organizations, which are subsequently analyzed thematically.

3.1. Participants

This study was conducted with a total of 25 participants representing 24 different business units in 23 companies. Two participants representing the same firm (AutoA) and business unit took part in the same interview. They are treated as a single participant in the coding. Two other participants represent the same company, but different independent business units of that firm (MachiB & D). They were interviewed separately and treated as two different firms in the coding. For the purpose of this study, only experts and leaders were interviewed who were estimated able to represent product development efforts at the organization and thus able to add value on the basis of their knowledge in the field (Mayer, 2013). The interviewees were asked to confirm that they can discuss product development at least in their unit. In one case, an interviewee suggested another person and only this second person is included in the data. Typically, the interviewees worked in positions such as heads of R&D departments or product development leads, and most, but not all, interviewees were men with engineering degrees. Table 1 summarizes the industry and size of the case companies, as well as which country either the company was based in or the country office in multinational organizations represented by the interviewee. The pseudonyms adopted for the companies reflect the industry and type of organization.

3.2. Data collection

The data was collected in the second half of 2020, when the participant companies had all experienced some form of restrictions and some reopening. Many of the companies operate in multiple countries, and thus the restrictions impacted the different companies or their business units or parts of teams at different times.

A semi-structured thematic interview guide was developed to prompt the participants' subjective experience regarding the pandemic. Three relevant questions were identified and sent to the participants at least a day before the interview:

(1) What influence did the COVID-19 pandemic have on product development, and how did you react to this event in the short term?
(2) How does this change the product development in the long term?
(3) Where and how can research contribute to enable these changes?

Table 1. Company profiles of all interviewees.

Pseudonym	Industry	Company size	Country
MachiA	Machinery and Plant engineering	Large	Finland
MachiB	Machinery and Plant engineering	Large	Finland
MachiC	Machinery and Plant engineering	Large	Finland
MachiD	Machinery and Plant engineering	Large	Finland
MachiE	Machinery and Plant engineering	Large	Germany
MachiF	Machinery and Plant engineering	Large	USA
MachiG	Machinery and Plant engineering	Medium	Germany
MachiH	Machinery and Plant engineering	Medium	Switzerland
MachiI	Machinery and Plant Engineering	Medium	Canada
MachiJ	Machinery and Plant engineering	Small	Germany
AeroA	Aerospace engineering	Large	Germany
AeroB	Aerospace engineering	Large	Germany
AutoA	Automotive parts	Large	Canada
ChemiA	Chemical and raw materials industry	Large	Germany
AeroCon	Consulting in Aerospace engineering	Medium	Germany
EleCon	Consulting in IT & Consumer Electronics	Large	Germany
DesCon	Design consultancy	Small	USA
MeDeCon	Design Consultancy in Pharma/Med Industry	Medium	Canada
EngSoft	Engineering software development	Medium	USA
SecurA	Security industry	Small	Canada
MediA	Medical Industry	Large	Finland
MediB	Medical Industry	Medium	USA
MediC	Medical Industry	Medium	Canada
MediD	Pharmaceutical/medical industry	Large	Finland

The interviews were conducted by several interviewers, who are also authors of this publication. It was explained to participants that the interviews were confidential and should focus on their own personal experience and perspective as R&D leaders in their company, rather than try to represent an official company line. The interviews were conducted via phone or online communication tools such as Zoom or Microsoft Teams. Further clarification and elaboration questions were asked, but thematically the entire interview was built around the three questions (Qu & Dumay 2011). Semi-structured thematic interviews were judged as the most appropriate data collection instrument, as we did not wish to limit in any way which type of influences and impact the participants might feel were relevant in their organization.

The interviews were conducted in two sets. First, a three-hour panel interview was organized with 10 participants on September 30th, 2020. In the panel, everyone was asked the same three questions, with the participants hearing others' responses to the same question before moving on to the next question. After this, 14 further individual interviews were arranged between October 2020 and January 2021. The individual interviews lasted for approximately half an hour each.

The panel discussion was conducted in English. The individual interviews were conducted in English, German or Finnish depending on the participants and the interviewer. Native language was used when possible, and a working language of the participants when this was not possible. The panel and individual interviews were either audio or video recorded and transcribed verbatim for analysis. All transcripts were anonymized before the analysis.

3.3. Data analysis

The interview transcriptions were analyzed in two rounds. First, the transcripts were read and coded deductively into three areas of reported impact on product development – immediate external effects (representing external uncertainties), adaptive action already taken by the case companies in response to the pandemic (representing internal responses to uncertainty), and longer-term plans and concerns for changes not yet realized (representing mainly internal uncertainties). Within each of these areas, responses were first deductively coded into the three areas of impact in product development – level of innovation (what), processes (how), and resourcing (who) – identified in the literature review. This coding was done by three of the authors. To ensure common understanding across coders, five protocols were coded by all three coders in the beginning, where any discrepancies were discussed until consensus was reached. After that, the transcripts were coded by either one or two coders.

In the second layer of coding, responses within each impact area were inductively clustered based on their semantic-level thematic similarity (Braun and Clarke, 2006) to identify recurring themes in the responses. This clustering was done by one of the authors, and then shared and discussed. Different researchers might arrive at different categories – rather than aiming to identify universal categories, the analysis captures variation within the data, where examples and category descriptions served to clarify salient patterns within the data. The presence and distribution of themes across cases and categories were then compared to identify patterns of responses.

4. Results

Overall and unsurprisingly, many companies reported in late 2020 that their businesses were hit hard by the pandemic, most frequently citing lost sales and supply chain management challenges. For example, AutoA recounted

> '*since our world, which is 70 percent or more, the automotive industry came to a hard stop in March and April. That means all the [product development] projects that we worked on or most of them came to a stop. We had to shut down our facility for four weeks in this time*'.

ChemiA echoed the same common impact: ' *Corona had a really devastating effect. Business is really down*'. However, for a handful of companies, overall effects on the business had been smaller and, as expected, companies with medical or pharmaceutical relevant offerings (MediA, Medi D, DesCon, MachiI) reported increases in demand. For example, MediD described how in their business unit

> it just happened that we had a huge increase in demand. We are not talking about ventilators, but corona diagnostic kits.' Similarly, MediA supplied hospitals, which 'has kept us really busy. And in a way, we have had to find some really innovative solutions to how to serve hospitals and customers in a situation where demand suddenly surges.

However, nearly all companies reported the pandemic having already had some adverse effects on their product development (21/24; see, Table 2, below). In terms of resilience actions taken, a majority (16/24) were considering the longer-term effects of the pandemic and changes required to adapt their product development processes and a majority (16/24) had already made some changes to adapt the level of innovation, processes or resourcing of their product development efforts. We will next look into each of these in more detail.

4.1. Changes in the level of innovation (What)

For more than half of the interviewed companies (14 out of 24), the pandemic had had immediate effects on what projects would continue or what products would be developed. The balance of innovative vs. incremental efforts was the most frequently adjusted aspect of product development, with twelve companies adjusting their projects in response to the pandemic. Four companies sought to adapt to dropping sales by focusing on more incremental customer-driven development efforts. MachiA reflected that the worsened market situation had created increased pressure to say yes to customers, tying resources to customer cases rather than more strategic development. Similarly, MachiD turned to more incremental development as business units required quicker returns of profit amid diminished sales. MachiF, in turn, turned their focus more on local, incremental customer cases as material flows made operating with international research centers more cumbersome, and MachiE cut working hours throughout the company, necessitating a quick reprioritization and stopping of development projects.

Table 2. Summary of perceived impact on and adaptive actions in product development during the pandemic.

	Immediate external effects	Adaptive actions already taken	Future considerations
What- Level of innovation	Expected: Reduction in scope due to difficulty of accessing customers/materials. A few COVID-19 related industries saw a surge of demand. Unexpected: N/A	Expected: Reductions such as increased incremental and customer focus for quicker return on investment or reduced scope to wait it out. And pivot to COVID related opportunities where relevant Unexpected: Pivots and expansion to be more innovative. Some pivoted to leverage time created by pandemic, increased risk to respond to downturn, or extended scope to address new demands and opportunities brought on by COVID-19 even if not directly in an affected field.	Expected: Mainly concerns about maintaining: anticipating challenges, initiating new with less employee & customer interaction; Unexpected: A few examples of opposite plans to decrease or expand level of innovation.
How – Processes	Expected: Reduction in form of delays or slowdown observed, due to supply chain issues, difficulty in prototyping Unexpected: Mistakes took longer to discover	Expected: Increasing usage of virtual and hybrid prototyping solutions, prototyping at home office; piloting more fast and flexible processes. Unexpected: The forced change to virtual prototyping increased the demand for prototyping both from customers and the larger development team	Expected: Mainly looking to increase cycle speed and flexibility; further leveraging virtual testing and prototyping, and/or securing access to prototyping, customers and hybrid working Exploring means for virtual creative work and customer interaction One example of seeking to adhere more to standard milestones. Unexpected: N/A
Who – Resourcing	Expected: A few examples of being more dependent on local operations, a few mentions of consultants getting more outsourced requests Unexpected: Due to difficulty of virtual collaboration, more team independence or more local operations	Expected: Some examples of both reduction and expansion in type of resourcing observed. Some moved to more internal or localized due to material flow difficulties, dropped resources or reduced exposure to virus. Others moved to more open or collaborative to respond to increased demand or need to fill pipeline Unexpected: N/A	Expected: A few companies planning to change teams into more geographically distributed, smaller teams, seeking more co-development or development consortia Unexpected: Focus on human-human interactions and problems in social issues more than technology. Concerns about lower interaction quality effects on onboarding, initiating, engagement in product development.
Nothing reported	3 – EleCon, MachiC, EngSoft	8 – ChemiA, MachiB, MeDeCon, MediC, MediA, MediB, EngSoft, MachiG	2- SecurA, DesCon

However, while external uncertainties more often pushed toward incremental development, more companies sought to adapt by pivoting and increasing risk rather than reducing product development. SecurA, MachiC and DesCon all pivoted their offering to health and wellbeing areas or '*a little more COVID-proof*' (DesCon) industries. As MachiC, who does not work in a directly COVID related area, recounted, the pandemic acted as a spark for increasing efforts:

> Despite the challenges, and facing unplanned things, we were still able to, we immediately realized that this was also an opportunity, we can improve our customers' safety. [. . .] So in a quick pace, just in a few months, we developed this health and wellbeing offering, which had a range of completely new products.

Others, such as AeroCon and AeroA similarly pursued opportunities and demands created by new COVID-19 regulations in their field. For example, AeroCon recounts

> We have initiated the short-term development projects in order to adapt the products that are established in aviation to the requirements of the corona pandemic and hygiene requirements [. . .] That means, in principle, we have more of a product innovation in the existing product.

The uncertainty also caused many firms (8 out of 24) to be concerned over their ability to create new ideas and products (EleCon, MachiB, MachiH, ChemiA, AutoA, MediD, SecurA, MeDeCon). For example, ChemiA reporting a 90% drop in invention disclosures submitted by employees:

> I think this is directly related to mentality or to the personal effect that the pandemic has on our colleagues. That they really go into all that, that they are trying to reach safe harbors, that they are trying to fence what they have and not step out of the group to show themselves too much. I think this is somehow related to that.

SecurA, MeDeCon and MediA, on the other hand saw the lack of unplanned '*water cooler*' or '*coffee pot*' discussions hindering innovation. MediA was exploring means to overcome that via virtual boards. Others (AutoA, MediD, SecuraA, MachiH) were actively exploring the use of virtual means, but to hold planned creative sessions.

Unexpectedly, three firms saw the pandemic also as an opportunity for innovation. MachiI reports:

> But what we have done internally is where we find we need to work on projects, and it has gotten a little slower, if our engineers have extra time internally, they're working on other projects that will help us estimate and give us better customer service in the future.

Similarly, with AutoA management had pushed for proactively identifying new technologies and concepts,

> since the projects were on hold, we were looking for new projects, and we were also looking for ways to keep our people busy. [. . .] And this was kind of management driven and kept us kind of busy and also productive and gave us also an advantage in terms of competitiveness against others. So, we had some good inventions in the last six months, which we would never had before.

Finally, MachiA saw increasing the level of innovation as a way to tackle the downturn. They increased their schedule and timing risk, selling a radical leap in product performance prior to having developed the solution.

The data does not indicate if the remaining 14 firms were able to maintain their level of creativity, as level of innovation was not referred to during these interviews, with the interviewees focusing on other effects and actions.

Longer term considerations in resilience in terms of level of innovation were rarer. ChemiA anticipated shifting to more incremental work to secure faster commercialization and revenue going forward (similar to MachiD):

> We had or tried to have a share of 70 percent incremental innovation, 20 percent adjacent innovation and 10 percent of radical innovation. When it comes to how to split the R&D funding. And we see a huge shift in that. And I think now we will end up with the funding of 90 percent of incremental innovation, maybe 10 percent of adjacent innovation, that we will keep for some time at least. We will stop the radical and disruptive innovation. This will have a major impact on our product development.

AeroA was also looking to pursue more projects but of smaller size to decrease risk. In contrast, AeroB was looking into more ecosystem and customer-oriented development, as well as expanding into new areas brought by COVID-19 regulations.

In addition to explicitly focusing ongoing for safer, more incremental innovations or riskier, more radical innovations, several companies reported concerns over their ability to innovate. Initiating new projects without live interaction amongst employees or customers would become a challenge in the face of a prolonged pandemic, but few had plans on how to tackle this yet. In contrast, MediD saw their quick scale up during the pandemic as '*not quite as a moonshot*', but as an encouraging benchmark of how a focused effort yielded results that could catalyze further ambitions.

4.2. Changes in product development processes (How)

Product development processes were immediately affected by the pandemic for two thirds of the case companies. The reported external uncertainties were typically different types of delays. Seven companies noted slowdowns in their development cycles due to delayed feedback and decreased interaction quality in remote operations, waiting for components or challenges in collaborative prototyping. Beyond the expected delays, the lack of interaction led to e.g. noticing mistakes later than normally. MediA describes design engineers sitting on a problem longer without asking or realizing to ask for help and MachiG describes the difficulty of inspecting a part from documents rather than seeing it on their desk. These challenges resulted in a need for creativity in adapting their ways of working and processes. Although the changes were sudden and forced, MachiD mentions they were pleased to notice that such creative process changes are possible when necessary. MediD, who unlike most firms, faced significant increase in demand, also saw the forced changes in their processes as a benchmark for the normal times of '*what is possible with focused effort*'.

Prototyping was the most mentioned area that was impacted significantly. For example, MachiE reported development cycles having lengthened due to the challenges in travel and face-to-face meeting delaying access to physical prototypes:

> One of the biggest challenges we had, like already mentioned, is putting in the prototypes and going down and seeing what's happening and figuring out how to solve that. That was now way more complicated.

Delays could also be caused by supply challenges in components (SecurA & DesCon) or delays in getting them to customer sites (MediB). For example, DesCon lamented that

> prototype delivery timelines are much longer and a lot less predictable, because you think a place is gonna be there and it can fit you in, but then they can't.

Interestingly, we find that the difficulty in prototyping led to firms exploring creative means of replacing either the physical interaction with prototypes or the prototypes themselves by virtual means. However, it is worth noting that some companies (DesCon, MachiD) were able to continue prototyping with their traditional use of virtual tools and (ChemiA) with digital twins. AeroA, on the other hand, adapted to using 3D-printing as a rapid-prototyping method and combined these physical prototypes with virtual mockups (e.g. Videos or PowerPoint mock-ups) to be able to demonstrate their ideas to customers remotely. MachiH had increased virtual meetings with customers compared to previous visits manyfold. MeDeCon, in turn, reported bringing prototyping into home offices:

> Through our large spread all over the greater [local] area there are lots of ventilators in people's basements right now as they have been building and testing the units there themselves.

Further, MachiD had already been using 360-degree cameras and now expanded their use for remote client approvals in the absence of site visits. Similarly, MachiC described how required audits had been moved online to video streams of prototypes and internal sharing of prototypes had even increased through moving operations online:

> We've had these virtual demos, actually, for the first time. So we circled around our prototypes, shot videos of them, what we've been doing during Covid-19, and then streamed them to the entire organization. And we actually got extremely positive feedback, that this is something we absolutely want to continue in the future regardless of whether we can meet physically or not. This way we can ensure that everyone globally knows what is being done where, and we got a lot of good feedback on it.

In addition to being able to continue prototyping amidst the pandemic, MachiF noted increased customer demand for prototyping with '*more desire to push us to have prototypes available to them to use*', and AeroB quicker cycles due to the shift to digital and distributed collaboration, opposite of what most firms experienced.

In addition to adapting prototyping processes and tools, some companies had adjusted in the overall development process. MachiA had moved into a quicker cycle speed, increasing the risk they were taking before the pandemic through selling a radical leap in delivering to customers earlier in the development cycle. With increased pressure to cater to customer demands, MachiB, in turn, had sped up their development process in a reduced form of '*not quite a full development*' cycle. MachiC, entering a new COVID-19 related offering category, had also adopted a new process, '*really lean and agile development, to allow us to get this quickly to the market*'. This included, for example, seeking customer feedback earlier on in the process, which represented a concrete step toward implementing their strategy of becoming a more customer-centric company.

While most companies had not yet adapted their processes on a larger scale, many were considering longer term changes to development processes. MachiF reported a need to reduce their product development cycle length, launching a pilot group for jumping over phases or gates. Working in an industry where projects were measured in years, they also emphasized the need to plan for uncertainty, trying to find ways of working which would accommodate unexpected disruptions mid-cycle. MachiE, MeDeCon and AeroA echoed this sentiment – agile and more flexible processes would be needed to react fast to uncertain changes in long cycles. They had started reexamining processes and were engaged in scenario work, but changes had not yet been made. For MachiC, the desire for faster cycles was coupled with goals of increasing experimentation and customer involvement. In contrast to these four organizations seeking more flexibility, MediC – facing a quick spike in demand – felt an increased need to adhere to timelines and milestones.

Prototyping and testing also remained key concerns going forward in adapting to the pandemic. AutoA, MeDeCon, MediA, MediC, MachiC, MachiG and MachiJ were all considering ways to secure easy access to prototyping and testing and further improving virtual approaches. Many had found ways of making it work remotely, with for example, doctors '*being guided virtually by [MediC's] specialists to run the system step by step*'. DesCon recounted leveraging existing networks and

> We worked very closely with a number of key opinion leaders, respiratory therapists who we had in our network previously. And it was all by video. So, the designers would sit, and they would show drawings and say what do you think about this user interface? They would show cardboard. What do you think of this? Then they showed the first prototypes that we made. What do you think of this? So, here's a specific detail. [. . .]. But we did a lot of prototyping, tested them ourselves, worked with our local people.

However, companies that had already tested out new ways were typically eager to find further solutions for effective remote testing.

Besides prototyping, several companies reported concerns of difficulties in the earlier process phases, namely customer and user interaction (MachiI, MediA) and creative ideation (EleCon, MachiB. AutoA, MediD). Some companies, like SecurA and MachiH, were seeking further virtual replacements to ideation and creative collaboration, whereas others, such as EleCon, were looking for creative ways to enable more physical encounters to help kick off projects and initiate new ideas.

Furthermore, MachiI was concerned how they might mitigate the adverse effects of reduced customer interactions with drastically reduced customer site visits and canceled trade shows.

4.3. Changes in product development resourcing (Who)

Resourcing was the least commonly affected or acted upon dimension within product development brought up by the 24 business units of 23 case companies, but many were considering the longer-term effects that the pandemic would have on resourcing.

As external uncertainties the travel restrictions in place had necessitated AutoA to adopt more localized operations, with units being more self-reliant and requesting less help. AutoA explained that

> there is a group or a team that normally travels to other divisions in assisting on new products or debugging. This became online, but with limited. What it did show us, and we've noticed this from the technical side here, is that the divisions and the individuals at that location became a lot more independent and not so much relying on these individuals to come down and help them.

In a similar vein, teams had become more isolated in MachiG, where avoiding spreading the virus had cut cross-team and cross-functional talks. On the other hand, the design consultancy DesCon reported that they had arrived to an advantageous position with many other companies wanting to shift into more local operations:

> Because clients tend to want to stay local and they like the idea, our clients like the idea of a small company that can fit with them as opposed to a larger company, like a larger design firm that may try to like shove a process down their throat or something.

Only MachiE reported an immediate challenge in product development resourcing through having had difficulties bringing in newer team members in remote working; however, this sentiment was echoed by many others considering the longer-term impact of the pandemic and particularly the remote working it entailed.

The ten companies that had already taken some adaptive actions in the arena of resourcing had all reported the pandemic having had some sort of external impact on their product development, typically in terms of their level of innovation and/or processes. Here, we could see different responses: AeroB, MachiD and MachiF moved toward more internal operations to adapt to the pandemic, whereas AeroA, MediD and ChemiA reported bringing in more collaborators. For MachiD, the move to more internal work was connected to a decrease in demand, making insourcing a more desirable option than outsourcing. Demonstrating a similar logic, the *spike* in demand for MediD pushed the pharmaceutical company toward more *external* collaboration:

> We started to operate in a completely new way. [. . .] We had to conclude that we need to open up our closed business, and have to let others manufacture things that we would have never on Earth allowed anyone else to do a year ago.

For MachiF, in turn, the rationale for moving into more internal and local operations was connected to decreasing the risk of COVID-19 infections through limiting people flow and as a response to difficulties in material flow – transporting necessary materials was no longer quick and easy, discouraging the use of distributed operations in product development. In contrast, another large industrial manufacturing company, ChemiA, reported that the pandemic had supported their shift to collaborate with startups and

> fill the funnel' for development through 'try[ing] to generate innovation or invention at the first point with external partners, with co-creation.

Finally, AeroCon, MachiE, and MachiI reported reducing personnel for product development. MachiE decreased working hours for product development staff to reduce running personnel costs in response to reduced sales, in the hopes of safeguarding against the need to lay off people down the line. AeroCon, in turn, had cut both employees and entire development departments due to reduced demand. MachiI had also introduced a temporary voluntary 20% work time reduction and pay cuts after a few months of slow sales but had already moved back to full time operations despite business still being somewhat slower than usual.

Considering longer term resilience, MachiF was considering adopting smaller teams in addition to having already shifted to more localized and internal operations to speed up product development. However, most longer-term concerns for resourcing focused on the breadth, quality, and pipeline of creative ideas rather than speed of execution. MediB was considering doing more co-development, responding to

> these smaller, really innovative companies, they really want to do a lot of co-development. And I think that those are the ones that we've found the most fruitful, right, in solving problems out there for the customer, the patient.

AeroA was looking to form larger consortiums to address new regulations in the field, and AeroCon felt more specialists would be needed in the future to be able to achieve goals (e.g. climate goals). However, the predominant theme was concern rather than action plans on how the companies might adapt to the longer term effects of virtual and distributed teaming. Onboarding, maintaining engagement and creativity, sparking new ideas and initiating new efforts were seen to be more challenging in remote operations, with more limited and narrow interaction carrying severe long term implications for product development success. For example, EngSoft reflected that

> the biggest challenge was, has been and will be, really, to ... to have coherent teams that, you know, can develop really trusted collaboration in spite of never really meeting in person.

ChemiA discussed a need to encourage creative collaboration by having better office spaces, while also increasing remote work for more focused tasks. MachiB shares similar future plans

> we will go back to this face to face meeting to some extent that it used to be. But I think that we need to have a more, more balanced way of doing between this type of social networking and personal relationships and then the spiritual ones and how we split and also give the people the opportunity to have time for their family and support their thinking on under this aspect, whether it was creating good ideas and developing things.

Many connected these challenges to lower interaction quality, often attributed to a less immersive interaction experience leading to lesser feedback and informal interaction. For example, MediA reported already seeing that the threshold for seeking help has increased, slowing down the detection and solving of issues:

> When people work there on their own desks, the threshold to connect and ask, and that type of spontaneous joint problem-solving, there isn't any. Then when people try to solve those problems on their own, it can lead to a pretty deep pit. And when it finally becomes clear that hey, we have a problem, and that person has tried to alone solve it, and no one has really realized that we really have a problem, then it's a pretty difficult road to climb out of that pit.

MeDeCon echoed the concern of lower feedback quality, connecting it to overall team effectiveness.

> And then it seems like you've normed, but you haven't. I think probably in person, it's also easy to pretend like you've normed. But it's not so easy. You know, someone turns off their camera. You can't tell if they're working elsewhere or getting something done or have a coffee, or they hate you. While, if you're in the room, you can tell if someone hates you and hates what you're doing. And so, it's easier to kid yourself that you've normed when you haven't.

Most companies saw bringing back some face-to-face interaction into the mixture to complement remote working as a potential solution for increasing interaction quality. Plans to leverage the new situation to increase resilience compared to pre-pandemic conditions through resourcing were rare, with an exception coming from MachiD, anticipating increasing team diversity due to remote working, enabling more virtual development teams across Europe and Asia going forward.

4.4. Lack of effects, actions or longer term considerations in product development

Only three companies reported no immediate effects in product development, with for example, EngSoft remarking

> I think it had actually amazingly little, in some sense, weight on the product development. I mean, on business intervals and lots of other things, it did have a significant impact. On product development itself, not so much.

Correspondingly, EngSoft did not report having engaged in adaptive actions in their product development. However, a further seven companies had not sought any adaptive changes in their product development, despite having been affected in one (MediB, MediC) or two (MachiB, MachiC, MachiG, MeDeCon, MediA) of the three areas of what, how and who in product development. All these cases, however, were considering the longer-term effects and/or actions to take to address these effects.

Only the startup SecurA and design company DesCon reported no longer term effects or plans for action in changing their level of innovation, processes, or resources, despite the startup having already pivoted into COVID-19 relevant offerings and clientele of the consultancy being adjusted through demand. Combined with having already acted, the lack of longer-term considerations for changes to increase resiliency could possibly reflect a shorter time horizon in planning, influenced by the younger age of the startup company and shifting nature of client projects in the consultancy.

5. Discussion

The current study investigated how the onset of COVID-19 has impacted product development, and how companies have responded to these effects. Based on 25 interviews of practicing product development experts in 23 companies, we find most underwent significant changes, but the directional results were mixed. Surprisingly, the mixed reactions are not necessarily due to the firm or industry type. We did see more positive external effects for the firms in the medical device industry as expected, but interestingly firms in Aerospace or Machinery and Plant engineering demonstrated opposite reactions to the onset of COVID-19. Almost all companies made some changes in product development, either in terms of the level of innovation, processes and resourcing, with surprising variation and patterns emerging.

In terms of the level of innovation sought through product development, we saw a mixture of reduction, expansion, and pivoting responses, with no clear pattern observed in terms of the extent or scope of impact of the pandemic on these organizations. For example, expanding to more radical levels of innovation or redirecting efforts to new opportunities were observed both amongst companies reporting being hard hit by the pandemic and affected to a lesser degree. While past research has found customer and competitor focus to have a positive impact on innovation (Calantone et al., 2010; Roper & Tapinos, 2016), in the current study, an increased focus on customers was sometimes coupled with expanding into new areas (such as AeroB tackling new COVID-19 related needs), whereas in other instances the customer-focus tied efforts to incremental, short-term efforts for quicker returns (e.g. MachiD). Similarly, the expansions and pivots varied in whether they were related to direct COVID-19 needs and opportunities (such as detection, prevention, and treatment of the disease), indirect changes brought forth by the pandemic (such as increasing investments into wellbeing and remote solutions and local operations) or unrelated to the pandemic (such as utilizing freed up time for long-term strategic, internal development). The results highlight the diversity of adaptive internal choices available in response to external uncertainties and events, but more research is still needed on how these influence longer term resilience.

For a significant subset of the companies, business was, as expected, negatively impacted at the time. A fifth of the studied companies reduced their product development due to loss of sales from COVID-19 or adopted a more frugal approach to product development. Indeed, past research suggests instability can shift the radical/incremental balance toward incremental innovation (Chao

& Kavadias, 2008; Chao et al., 2009), as could be seen with for example, in MachiD and ChemiA. Companies like AeroCon and MachiI, in turn, were aimed for resilience through frugality (Giones et al., 2020), conserving resources and carefully thinking the economic rationale for expanding new resources. Reduction approaches could also be seen in cutting external and international collaboration, limiting who in addition to what and how. Interestingly, unlike companies adopting expansion and pivoting responses, those responding predominately in reduction measures were more unified in how they saw the pandemic, namely as a temporary disturbance, even if unknown in its length. Reduction approaches were rarely coupled with having taken longer term actions to adapt, even though the organizations were considering various longer term possibilities. As the current study relied on cross-sectional interview data, it is unclear how the continuing pandemic might influence the prevalence of reduction approaches. Neither is it clear under which circumstances expansion, redirection or reduction responses would have the most favorable effects on short-term and long-term performance. Further studies are needed to examine the longitudinal effects of initial and long-term responses.

A useful framework for such studies might include consideration of how constraints on development are faced and reframed (Dorst, 2011). Reframing is known to be a key part of the design process and one of the characteristics of design expertise (Darke, 1979; Schön, 1983; Lloyd and Scott, 1995; Cross, 2004; Björklund, 2013). The uncertainty introduced by the pandemic introduced several new constraints and ambiguous cues for the organizations. Even in normal times, design and engineering problems vary enormously by how constrained they are. Engineering problems are often at least partially over constrained and form a complex network of opposing drivers (Stacey & Eckert, 2010). Here, both the added constraints by the pandemic, limiting for example, supply availability, as well as the added ambiguity of quick changes and uncertain projections dramatically changed the problem space for product development. On one hand, added constraints can increase creativity, (Finke et al., 1992) but on the other hand, the added complexity and uncertainty emphasize the need for problem framing re-interpretation (Dorst, 2011). One reason for the high degree of variability in pandemic adaptations observed may be that these experts are used to reframing. As such, ambiguous and novel cues introduced by the pandemic triggered a wide range of novel problem interpretations and different responses in the range and level of innovation sought.

A more consistent finding compared to the changes in the level of innovation was that most companies had either responded or were planning to make changes in their product development processes to increase flexibility and decrease cycle length to better manage the heightened uncertainty brought forth by the pandemic. Indeed, more agile, flexible, and responsive approaches have been called for (Albers et al., 2019; Atzberger & Paetzold 2019; Hölttä-Otto et al., 2008; Sinha et al., 2020). The pandemic can be seen to have amplified some trends that had already started before the pandemic (see, Isaksson & Eckert, 2020), moving away from the traditional stage gate processes toward more flexible way of working at least temporarily and taking further advantage of virtual reality models and rapidly manufactured prototypes for evaluation. Elsewhere, Ahlstrom and Wang (2021) have observed a shift from cost-based strategies to time-based strategies due to COVID-19. Similarly, the opportunities of VR in design have been reported before (Hu & Georgiev, 2020) but the pandemic has spurred more trials and experiments in using these (e.g. Truong et al., 2021). Most cases in the current study reported new use of virtual tools to increase flexibility of location, and adoption of new digital tools. Interestingly, these changes were observed in many cases to increase the demand for prototyping, both in-house and by clients. COVID-19 forced the adaptations or opened up discussions for new agile processes and potential for virtual prototyping and even validation, but it remains to be seen if this will become common practice also after the pandemic. While some early research on using more agile processes in (non-software) product development has emerged (Ahmed-Kristensen & Daalhuizen, 2015; Albers et al., 2020; Peterson & Summers, 2021), more research is needed on flexible processes for product development, and especially on digital tools and methods to support it.

An even larger amplification of trends than the shift to agile processes, however, can be seen in the general way of working and the implications this had for product development. In terms of resourcing, challenges brought by the pandemic surprisingly could both prompt wider collaboration and promote more independent and localized operations. Further, the loss of face-to-face and unintended interactions is an interesting unintended consequence of the disruption, prompting concern from almost all studied companies on its prolonged effects, but few had acted and plans for addressing the issue. Lower interaction quality was seen as a concern especially related to starting new creative initiatives and finding new customers with the less ad hoc and informal interactions taking place. Further, idea generation was down in some firms. Some discussed how that could be due to the overall spirit of the workplace and need to keep up with the social aspect of work as well, which is well in line with recent work proposing creative design as a social practice (Richter & Allert, 2016). Richter and Allert (2016) posit that collaborative design is not only problem-solving, but it is a socio-cultural process. This was also echoed by our participants. The issues in creative initiatives could also be due to the organizational innovation culture and values (Russell & Russell, 1992) or the creative personality type of the people involved (Guenther et al., 2021), but this data was not collected in this study.) Product development processes were slowed down partially due to increased difficulties in noticing problems and exchanging ideas. Further, team members were more prone to solving problems in isolation rather than as a team, and more prone to rely on their own informal networks, which resulted in further quality issues and delays. Resourcing was further affected by frequent difficulties in onboarding during remote work. These concerns and observations highlight the role of informal and ad hoc interactions in product development, and how their reduction seems to have an unintended effect in shifting product development toward more execution and less initiation and generation. As such, studying the role of informal action posits a promising avenue for further research. For example, future research could explore whether the balance of exploration and exploitation (March, 1991) changes with different degrees of hybrid working or with different frequencies of serendipitous encounters within product development. On the other hand, studies could also examine how different degrees of informal interaction in internal product development operations and with customers and collaborators influence organizational resiliency, as McDermott (1999) found the importance of informal networks is heightened during times of uncertainty. The current results suggest that while planned interactions can be easily replaced with virtual tools, the unplanned interactions are harder to replace but can have significant consequences on development efforts. As such, we call for models that incorporate unintended interaction in addition to designed scope, process, and resourcing to be able to better understand and prepare for product development resiliency during uncertainty.

6. Conclusion

In summary, we find some straightforward external impacts and reactions of COVID-19, such as those in a COVID-19 related area experiencing a spike in demand for development and those in airline industry suffering a halt in their sales and consequent reduction in development. However, we also find that similar sized firms in non-COVID-19 related areas reacted in surprisingly opposite ways. While for most, the onset of the pandemic was a financial hit and time of great uncertainty, some chose to use the time to take risks and invest in creative efforts, while others chose to rather wait out the storm. What was consistent was change, few kept the status quo of development levels, processes and resourcing. It will be interesting to see in the long term how the opposite strategies play out. Similarly, it will be interesting to see if the more agile processes that most firms mentioned as a future consideration take hold and if the forced global experiment on working remotely and starting new creative efforts and teams remotely will result in new abilities to continue doing product development remotely. The COVID-19 crisis has given companies the opportunity to evaluate their ways and working and to retain those aspects that have worked from them and will enable them to be innovative in the future.

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