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Accelerated innovation in crises: The role of collaboration in the development of alternative ventilators during the COVID-19 pandemic

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ABSTRACT

This article discusses the need for accelerated innovation in crisis situations and argues that collaboration plays an important role in enabling such acceleration. The central research question is: How can innovation efforts during crises be accelerated, and what role does collaboration play? We draw on a phenomenon-driven, in-depth qualitative case study of seven initiatives that have developed alternative ventilators in the Netherlands during the COVID-19 crisis. Our results highlight how the COVID-19 pandemic has created a relatively short crisis window of opportunity for accelerated innovation processes that is driven by the urgency to develop solutions to the challenge at hand. Importantly, we show that when collaborative initiatives join other collaborative initiatives—what we define as nested collaboration—a forum for coordinated knowledge and resource exchange between the initiatives is created, increasing the potential for learning and accelerating the innovation process. Finally, we find that purpose is an important intermediating mechanism to accelerate innovation as it enables non-competitive collaboration between the initiatives in favor of the public good. Our results have important implications for accelerated innovation processes to achieve societal missions, goals, or challenges.

1. Introduction

The rapid spread of the coronavirus COVID-19 has uncovered an interesting conundrum in innovation processes. We already know the importance of innovation in responding to and recovering from challenges such as pandemics: worldwide, numerous medical and health innovations are rapidly being developed, tested, and introduced [1–3], including testing methods, protection materials, contact tracing apps, and vaccine or ventilator developments. With the pandemic ongoing, such processes need to produce innovations significantly faster than before. The conundrum is that existing innovation research tells us that, across different organizations and industries, innovation and new product development (NPD) processes take time [4–7]. Moreover, time pressure on innovation processes and their phases, milestones, and cycles is generally believed to be detrimental for innovation [8–10], creating the feeling of having too much to do in too little time [10].

Still, an emerging stream of literature focuses on the acceleration of work and innovation processes and its consequences [3,11–13]. New technologies and innovation processes, such as 3D printing and hackathons, accelerate innovation activities from a journey into a sprint [11, 14]. Increasingly, these studies even indicate such accelerated development can produce successful innovations, despite the time pressure [3,11,14–16]. Hence, there is a need to explore the role of time in innovation processes beyond its association with pressure or typical organizational settings with clear temporal structures.

In this sense, the COVID-19 pandemic represents an excellent opportunity as it presents new temporal conditions that have not yet been studied. Furthermore, the sudden appearance and spread of COVID-19 has increased the articulation of crisis and thus the need to act, change, reform, or, most importantly, innovate rapidly [17–19] to meet the demand for health innovations and solutions.

While research argues that acceleration of innovation and NPD plays a vital role in crisis management, there is no consensus on how best to kick-start and manage such accelerated innovation processes [20]. We argue that, to effectively tackle the problems generated by crises, there is a need for collaboration between multiple actors. We follow a stream of research that argues that collaborative innovation between companies, public bodies, research institutes, and governments plays an important role in finding solutions to wicked societal problems and needs [3, 21–24]. After all, collaboration brings together the knowledge and resources of multiple actors to accomplish a goal that might not be achieved by a single actor [25]. In addition, joining forces and involving the

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public can be a great source of support [24]. Cheshborough [17] therefore argues that the COVID-19 pandemic illustrates the benefits of mobilizing scientists, companies, research institutes, and governments to launch (open) collaborative efforts to innovate and find solutions to the problems generated by the crisis.

However, collaborative innovation processes take time. They take time not only to accrue knowledge and ideas for innovation [26] but also to establish trust among partners [27,28] or combine ideas from diverse fields [5,29,30]. Such collaboration has been especially complex during the COVID-19 crisis as people have been obliged to work in their own facilities, in different countries, and in different time zones and schedules [17] which do not necessarily fall easily into sync.

In this study, we bring together the two research lines of acceleration of innovation and collaboration to explore the role of collaborative efforts in accelerating innovation processes during a crisis. Our research question therefore is: How can innovation efforts during crises be accelerated, and what role does collaboration play?

To address this question, we draw from an in-depth qualitative case study of the innovation efforts to rapidly develop alternative ventilators in the Netherlands during the COVID-19 crisis. In response to the imminent shortage and altered demand for ventilators during COVID-19, several Dutch initiatives—companies, student teams, and partnerships—acted to rapidly develop, produce, and deliver alternative ventilators to hospitals. This article focuses on the development processes of those various initiatives.

Our results indicate that urgency creates a relatively short crisis window of opportunity that triggers accelerated innovation processes to meet the demand for new products in mature industries like the medical industry for ventilators. This window is, however, relatively short; as soon as the urgency of the crisis diminishes, the need for innovative solutions also decreases. Our results support our premise that, within the crisis window of opportunity, collaboration plays an important role in enabling acceleration of the innovation process. However, it is important to note that collaboration per se—simply bringing together different disciplines to enhance the knowledge and resources that individual initiatives lack—does not necessarily accelerate the development of innovative products. Instead, we show that when collaborative initiatives unite with other collaborative initiatives in nested collaboration, a forum for coordinated knowledge and resource exchange between the initiatives is created, increasing the learning potential and accelerating the innovation process. Finally, we find that purpose is an important intermediating mechanism to accelerate innovation by deprioritizing competitive advantage or monetary benefits in favor of the public good and thus enabling non-competitive collaboration between the initiatives. We conclude our study by discussing what lessons might be learned from the experience of accelerated innovation in the COVID-19 pandemic.

2. Theoretical framework

One of the key issues in the field of technology and innovation management is how new technological solutions originate and evolve in society [31–34], and how they are challenged by threats, crises, and other emergencies such as environmental disasters, wars, or pandemics—that is, examining how crises can be the origin of discontinuity rather than technological breakthroughs [31]. Furthermore, during such crises, time is of the essence: Society is desperately seeking actors with R&D capabilities to innovate in short timeframes to meet the ‘grand challenge’ and prevent a worst-case scenario. Conventional innovation processes, which tend to be time-consuming, expensive, and respond to known problems, are often inadequate for uncertain and unforeseen circumstances [35]. In this study, we therefore explore how innovation processes during crises can be accelerated, and argue that collaboration plays a vital role.

2.1. Crisis management and the role of innovation

Within the field of technology and innovation management, crisis management seeks to address key issues that arise when market disruptions or crises (i.e., war or economic downturns) create high urgency and uncertainty [36–40]. Crisis management aims to limit the damage caused by crises by focusing on prevention and preparation before a crisis, response during a crisis, and reflection and learning after a crisis [37]. The assumption is that problems created by a crisis cannot be solved by ad hoc innovations but, despite the urgency and uncertainty of the crisis, a systematic, coordinated, and planned approach is required [38,40,41].

Innovation plays a vital role in crisis management [20,36,39]. That is, a crisis provides favorable conditions for generating innovative technological solutions or exploring alternative approaches, which might diffuse more widely due to changes in demand [1,18,36] or user preferences [2,18]. Coccia [42,43] further argues that crises are important sources of problem-solving activities that drive the development of innovative technological solutions for competitive advantage.

The debate about the role of innovation in managing crises continues in the current COVID-19 pandemic. In contrast to the crisis management literature, however, innovation activities to address COVID-19 have been numerous, involving high levels of improvisation and experimentation, and have been performed with dedication under conditions of extreme uncertainty and within tight timeframes [35,44,45]. This emphasis on time and the need to find solutions quickly represents something of a conundrum. Existing research generally tells us that innovation and NPD processes take time, but the sudden appearance and spread of COVID-19 has increased articulations of crisis and the need to act, reform, and, most importantly, innovate quickly [3,18,19]. The pandemic has thus required accelerated innovation processes to find solutions to the wicked problems created by the COVID-19 crisis.

2.2. Crisis management, innovation, and the need for acceleration

Time plays a central role in innovation research [4,12,46]. Across different organizations and industries, research emphasizes that significant periods of time are associated with the innovation process [5–7]. That is, innovation is knowledge intensive [26] and involves high levels of technological uncertainty [47]. As such, innovation processes tend to be framed as time-intensive “journeys” [7] or “cycles” [48] that follow a non-linear path [6], sometimes taking years to complete [49].

Moreover, time pressure is generally believed to be detrimental for innovation [5,10]. Most organizational contexts have clear temporal structures around which employees structure their daily routines [46,50,51]. Within those organizations, innovation processes usually follow a clear path with phases, milestones, and cycles [5,50,52,53]. Time pressure, which aims to accelerate the innovation process, tends to generate feelings of time famine: having much to do in too little time

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1 In this paper, we introduce the concept of a crisis window of opportunity. The more acknowledged concept window of opportunity relates to research around entry-timing advantages. After initial discussions on pioneering advantages for firms (see e.g. Refs. [70–72]), extant research generally associates high firm performance with entry during a window of opportunity that occurs between the emergence of a dominant category [73] and the emergence of a dominant design [74]: p. 6213; see also [31,33,48]. We argue for the existence of a crisis window of opportunity that emerges only in crises or emergencies (i.e., wars, economic downturns, natural disasters) once a dominant category and design has been established, such as in mature industries. That is, the crisis challenges dominant designs based on newly emerging needs and requirements. The crisis window of opportunity is inherently bound to the crisis at hand, meaning that as soon as the crisis is resolved or is under control, the window closes.

2 A ‘grand challenge’ is any important, complex, or ‘wicked’ societal problem with a high likelihood of global societal impact [75]; p. 1881.
Time famine is detrimental to work performance, especially for creative and innovative processes, as it requires to reduce ambiguity and create certainty [8,9,54,55]. Furthermore, Reinecke and Ansari [51] argue that although a linear, clock-time orientation towards time management is meant to enhance efficiency, coordination, and control, it is unsuitable for managing emergent, complex, and open-ended processes - as in the case of innovation during the COVID-19 pandemic.

Still, an emerging stream of literature focuses on the acceleration of work and innovation processes and its consequences [3,11–13,56,57]. The study of Lifshitz-Assaf et al. [11]; for instance, emphasizes that new product development technologies such as 3D printing, new innovation processes such as (open) hackathons, or new societal circumstances such as those introduced by COVID-19, all enable the acceleration of some innovative development activities from a journey into a sprint. Indeed, studies of new technologies like 3D printing indicate that such technologies leapfrog the development time of new products [3,58–60], and studies focusing on hackathons indicate that they successfully accelerate innovation [11,14–16].

These findings thus suggest there is a need to explore the role of time in innovation processes beyond its association with the typical time pressure or in common organizational settings with clear temporal structures. The COVID-19 pandemic presents an excellent opportunity to do so, not only because time is of the essence and even a slight acceleration of innovation can have significant benefits, but also because it provides an empirical setting without established temporal phases, milestones, structures, or daily routines. We therefore follow the development of new products—specifically alternative ventilators—to enhance our understanding of the accelerated innovation process.

### 2.3. Acceleration of innovation during COVID-19: the role of collaboration

While research thus argues that acceleration of innovation plays a vital role in crisis management, there is no consensus on how best to spur and manage such accelerated innovation processes [20]. Ardito et al. [44]; for instance, argue that the repurposing of artefacts, technologies, skills, and resources during the COVID-19 pandemic has spurred innovation. This corresponds with Gelijs and Rosenberg [61]; who indicate that a high percentage of new medical devices such as lasers, ultrasound, or spectroscopy did not emerge from (bio-)medical research but from technology transferred and modified from other fields (see also [62]).

Alternatively, Chesborough [17] suggests that open innovation could spur the mobilization of knowledge from different sources and accelerate the innovation process during a crisis. More generally, scholars have stressed the importance of collaboration and the need to involve multiple actors to handle complex and uncertain business environments [3,22,63–65]. Collaboration brings together the knowledge and resources (partly enabled by digital technologies) of multiple actors to accomplish a goal that might not be achieved by a single firm [25,65]. Furthermore, adopting an open and collaborative approach, joining forces, and involving the public can be a great source of support [24].

This line of research therefore argues that collaborative models involving companies, public bodies, research institutes, and governments are important in joint research and innovative technological developments aimed at tackling societal challenges [21,23,24]. Such joint initiatives enable diverse partners to join forces [21] and share broad external knowledge [24,66]. The current COVID-19 pandemic exemplifies this as it has prompted the rapid mobilization of scientists, companies, research institutes, entrepreneurs, and governments to collaboratively research and launch innovative solutions to the problems created by the virus [2,17].

Still, innovation and NPD processes, even when collaborative, take time. Such processes are knowledge intensive and it takes time to accrue knowledge [26] and trust [27,28] or combine ideas from different fields [5,29,30]. Furthermore, effective collaboration can be hampered by transaction costs and absorption problems that make it more time-consuming and costly than anticipated [66]. During the COVID-19 crisis, collaboration has been especially complex as people have been obliged to work in their own facilities, in different countries, and different time zones and schedules [17].

This produces an interesting conundrum. While research argues that innovation, and especially the acceleration of it, is vital in crisis management, there is no consensus on how best to manage such accelerated innovation processes. However, research also argues that collaboration could mobilize knowledge from different sources to accelerate innovation during a crisis, but combining knowledge takes time. In this study, we therefore combine these two important lines of research—on accelerated innovation and collaboration—to address the central research question: How can innovation efforts during crises be accelerated, and what role does collaboration play?

### 3. Study design

We conducted a phenomenon-driven, qualitative case study of seven initiatives—companies, student teams, and partnerships—who developed alternative ventilators in the Netherlands in response to the COVID-19 pandemic. We conducted the study in the Netherlands around the time of the first peak of infections and deaths (March 2020), creating a high need for ventilators to treat patients and save lives. We collected comparative data from multiple cases upon which we base our accounts of innovation processes in the development of alternative ventilators [67].

#### 3.1. Research context

Worldwide, seven large firms produce medical ventilators. The Dutch company Philips, with facilities in the United States, delivers the largest share of ventilators to the Netherlands, with system components coming from Europe and Asia. Other producers are Hamilton (Switzerland), Dräger (Germany), Vyaire (United States), Metronic (the Netherlands), and Shenzhen Mindray Bio Medical Electronics (China). Six of these producers together supply 80% of the world’s medical ventilators.

At the start of the pandemic, Philips, like many other medical suppliers, warned it would be unable to meet the (worldwide) demand for ventilators. Meanwhile, people feared that the countries in which such products are assembled (e.g., the USA for Philips) would protect their national interests and prohibit the export of medical supplies. The uncertainty of the pandemic and associated worldwide lockdowns caused supply chains to fail and delay the delivery of components. As a result, there was increased interest in maintaining national capacity to produce (alternative) ventilators, for which there was increased demand (see Fig. 1). Moreover, the hope was to develop simplified ventilators that could be operated by non-experts as well as ICU specialists, thus reducing dependency on trained professionals. The COVID-19 crisis thus inspired innovative solutions for low-cost and easy-to-use alternative ventilators.

3 The history of the development of ventilators is, actually, surprisingly long. That is, modern computer-controlled ventilators are relatively new, even though the basic principles on which they operate are more than a century old. In the 18th and 19th century, innovators produced so-called positive-pressure ventilation (forcing air directly into the lungs) and negative-pressure ventilation (changing the air pressure of the environment outside the body). The most famous invention based on this last ventilation method is, arguably, the Iron Lung, developed to treat polio patients during the 1920 polio epidemic. Nevertheless, developments in positive-pressure ventilation introduced in the early 20th century—such as the Pulmotor or the ‘rhythmic inflation apparatus’—eventually became the standard. These developments were spurred by, for instance, WWII fighter pilots’ need for oxygen masks during high altitude flights. Still, specifications such as tidal volume (how much air should be forced into patients’ lungs in each breath) was only introduced in 2000. For more details, see e.g., Refs. [76–79].
ventilators. This study explores, in real-time, the development of these alternative ventilators in the Netherlands.

For the core sample of our study, we identified seven initiatives that focused on developing alternative (emergency) medical ventilators in the Netherlands. We excluded initiatives that aimed to, for instance, modify existing designs so that two patients could share one ventilator (VU University Medical Center, Amsterdam), measure material fatigue in machines after prolonged use (TNO), or develop a digital platform where suppliers and demand can meet.

3.2. Sample and data: alternative ventilators in the Netherlands

Our results are drawn from an in-depth study of 7 initiatives that develop alternative ventilators in the Netherlands. Our core sample comprises two university-led initiatives, two public–private partnerships, and three private-led initiatives, supported by a network of suppliers. An overview of the different initiatives, and some of their characteristics, can be found in Table 1. The seven initiatives are all affiliated with the TNO center of excellence Brains4Corona, which connects the key initiatives for alternative ventilators with experts from different disciplines to accelerate the innovation process. Under the guidance of TNO, the lead authors organized interactive work sessions (N = 6) with initiatives and experts who have been selected via purposive sampling, to provide advice for the initiatives on the technological and societal challenges they faced.

We collected data using various qualitative research methods [67, 68] including interviews (N = 15), real-time observations during interactive work sessions (N = 6), reports and evaluations of those work sessions (N = 6), and news articles (N = 20). First, we conducted initial interviews to identify the core challenges the initiatives encountered when designing and developing their alternative ventilators. We used the insights from these initial interviews to develop work sessions in which experts from the company of the lead authors, TNO, and various external experts such as doctors, safety experts, and medical innovators helped the initiatives address those challenges. The initiatives and experts came together virtually over the course of six weeks to look for solutions and exchange experiences. We wrote reports and evaluations immediately after each meeting. We interviewed the various initiatives again at the end of the six weeks and collected (online) archival material. Table 2 provides an overview of our data sources.

3.3. Data analysis

We analyzed our data in two rounds. After conducting the initial set of interviews, we followed a grounded theory approach to analyze the data [86] and identify any themes representing the key challenges that the various initiatives faced and needed expert advice for. After discussing and comparing our initial findings, we identified four recurring and more focused themes for follow-up during the interactive work sessions: 1) the medical-technical needs and requirements for alternative ventilators, 2) the business case and the long-term perspective for alternative ventilators, 3) testing and certification of alternative ventilators, and 4) the production and supply chains of alternative ventilators.

In the second round of analyses, following the collaborative work and the second round of interviews, we analyzed the entire data set by following a comparative case study approach [67,68]. We started by coding the interviews in two rounds. First, in vivo coding, in which we collected and coded quotes and fragments of the text. Second, descriptive coding, where we summarized first-level codes in a short phrase or word. Finally, we abstracted the main subjects that influenced acceleration of the innovation process: urgency of the crisis situation, collaboration and exchange with other initiatives, and purpose (see Fig. 2 and Table 3).

Next, we wrote case narratives for each of the studied cases [67,69] that include an overview of the key events and developments during the innovation process, the collaboration, and the main success factors and challenges. We triangulated data in these narratives by utilizing the results from the analyzed interview data, the observational data, and the news articles. We then cross-compared the different cases within each narrative and between all narratives [67] to produce a general timeline of the innovation processes (see Fig. 3) and an overview of the trigger points for accelerating innovation (also plotted on a technology readiness level (TRL) timeline; see Fig. 4).

4. Results

Alternative ventilators were developed over four main phases that closely resemble the technology life cycle and include: 1) the experimentation phase, triggered by the COVID-19 pandemic; 2) the prototype development phase, in which alternative ventilator designs were developed; 3) the development phase, in which the initiatives tested and certified their products; and, 4) the production phase. All the initiatives started their NPD processes around the time of the first peak of COVID-19 infections and deaths in the Netherlands (March 2020), which created a crisis-bound window of opportunity. All the initiatives had their prototypes ready for development after an experimentation period of just two to three weeks. Diversification in the process only began in the development phase as initiatives looked to test and certify their prototypes for production. The Dutch Ministry of Health, Welfare and Sport demonstrated its support for two initiatives (Demcon and Operation Air) by pre-ordering 500 and 80 ventilators respectively, giving these initiatives access to a unique accelerated certification process for production. Other initiatives, however, had great difficulty in contacting the Ministry and were therefore unable to access the same accelerated certification process. As a result, three of the initiatives stopped their respective innovation processes mid testing. Two initiatives decided to continue development of their alternative ventilators to, among other things, help patients in countries who needed the innovations. Ultimately, only Demcon and Operation Air continued to the production phase in the Netherlands (Figs. 3 and 4) show the development of the initiatives along the TRL.

In the short crisis window of opportunity to develop a substitute ventilator, the different initiatives came up with at least three alternatives to the dominant design favored by large, established companies like Philips and thus effectively reinvented ‘the ventilator’: 1) a simplified version of the established ventilator, which only provides...
Table 1
Overview initiatives for alternative ventilators.

| Number | Name alternative ventilator | Initiatives | Design | Status | Product development | Production |
|--------|-----------------------------|-------------|--------|--------|---------------------|------------|
| 1      | VentilatorPal & FRD-e       | Freebreathing - Collaboration of companies Stogger, Cosmiconde, and Radboud University | Based upon MIT e-vent design | Active | Open source & private | Upscaling product | Potential for thousands |
| 2      | AllOne                      | Operation Air - Studentteam from TU Delft | Based upon Philips design | Semi-active | Open source | First product delivered | 80 pieces, with approval from Ministry of Health |
| 3      | HOAP                        | Project Open Air – Network of engineers and production companies | Based upon MIT e-vent design | Active | Open source | Prototype | No first product delivered |
| 4      | Project Inspiration         | Project Inspiration - Studententeam from TU Delft | Based upon historical design from Boerhaave museum | Active | Open Source | Prototype | 20 prototypes delivered |
| 5      | Ventilator machine          | Neitracco – engineering company | Based upon MIT e-vent design | Non-active | Prototype | No first product delivered | |
| 6      | Ventilator machine          | Dirty Boots - design company | Based upon MIT e-vent design | Non-active | Prototype | No first product delivered | |
| 7      | DemcAIR                     | Demcon – high-end technology supplier of product, supported by network of suppliers | Based upon own design | Active | Private | Upscaling product | 500 pieces, with approval from Ministry of Health |

*Disclaimer: status quo June 2020.

Table 2
Overview of collected data sources.

| Data type | Description | Insights |
|-----------|-------------|----------|
| Interviews | 15 interviews, 60 min each | Real-time and retrospective insights into the innovation sprint during the COVID-19 crisis from: Representatives seven initiatives, Six experts (medical-technical, business case national/international, certification, testing, production and supply chains) |
| Interactive work sessions | 6 interactive work sessions, 60 min each | Real-time observations of knowledge and experience exchange on the following subjects: Medical-technical challenges of emergency ventilators, The business case for emergency ventilators: market and long term perspective, Current challenges in certification and testing of emergency medical products (N = 2), Networks of production & design of supply chains in uncertain market(s), Reflection and looking forward |
| Reports and evaluations of work sessions | 6 reports and evaluations of work sessions | Main insights gained during the interactive work sessions and informal feedback |
| News articles | 20 news articles | Public accounts of innovation efforts of the various initiatives |

essential functions; 2) an emergency ventilator with only a bare minimum of functionality based on the open access design from MIT: E-vent⁴; and 3) a proprietary design.

Furthermore, the requirements created by COVID-19 produced quite broad variation in design, even among the initiatives that focused on the open MIT E-vent version. The MIT E-vent design comprises a manually compressed air balloon (the Ambu-bag⁵), which can not only be tiring to operate over time but also occupy a health professional who might be needed elsewhere. Hence, initiatives considered ways to mechanize or automate the hand-operated compression of the bag. Initiatives also considered closed rather than open systems to limit airborne transmission of the virus.

4.1. COVID-19 and the urgency to develop alternative ventilators quickly

Due to the unknown nature of the coronavirus and its ability to spread rapidly, the need for solutions right now is urgent. Normally, medical innovations take years to develop, but COVID-19 has imposed a much shorter timeframe. Therefore, it is necessary to accelerate a normally long innovation process and increase the pace of the innovation efforts within the crisis window of opportunity.

The different initiatives feel this urgency, but one of the challenges they face is striking a balance between developing their innovation as quickly as possible and taking the time to identify, for example, changing patient needs (i.e., the corona patient) or the wishes of the end user (i.e., the hospital). As one hospital expert described the situation: “We [hospitals] have been very busy with upscaling, and obtaining ventilators for COVID-19 was very important. However, at the time, we did not receive any guarantees from the existing suppliers. We are currently even waiting [5–28–2020] for some orders that we made in March 2020 still to be delivered. Thank God we did not need these deliveries in the end, but that was a very close call.”

Comparing the different processes indicates that some innovators prioritized technological innovation over identification of user needs. However, there is no evidence that skipping crucial steps in development saves time: Safety and deployment of alternative ventilators to Dutch hospitals remain the most important criteria. Other initiatives started with the identification of user needs, often in close collaboration with physicians and hospitals, but had to make technological adjustments along the way. For example, the Freebreathing initiative decided not to use an open source design due to safety concerns: “A company is not going to use its name on a self-built open source device if it would cost someone’s life” (Interview Freebreathing).

Uncertainty is a complicating factor in the relatively short timeframe for innovation in COVID-19 pandemic. This means that initiatives started the innovation process without established requirements for alternative equipment or conditions for market authorization. To illustrate, we refer to the importance of Article 11.13 of the EU’s medical device directive—designed for situations like COVID-19 but never used

⁴ For more details, see: https://e-vent.mit.edu/. The Ambu-bag is used by hospitals to provide air to a patient in emergency situations. These Ambu-bags are traditionally designed to be operated by hand, by a medical professional or emergency technician, by squeezing and releasing the flexible pouch. This is a task only for skilled and trained personnel, who can adjust the timing and pressure of the pumping based on the patient’s situation.
before—which indicates that a competent authority (the Dutch Ministry of Health, Welfare and Sport in this case) can initiate a process to accelerate the admission of medical devices to the market during crisis situations. The ministry is assisted in this process by an external expert panel and the notified body normally responsible for CE certification for medical devices in Europe and the Netherlands. Together, these bodies determine an accelerated admission procedure, dictating how many (clinical) tests must be carried out and how many documents must be assessed, while upholding the (#1) safety criterion for medical devices. Medical devices admitted through this accelerated procedure can be used only in exceptional circumstances, temporarily, and only for the Dutch market.

In practice, the accelerated procedure also presents challenges for the initiatives as they must effectively learn by doing. Operation Air, for example, was one of the first initiatives to start the accelerated admission process with the Ministry of Health, Welfare and Sport. It soon became clear that an accelerated route had not been clearly mapped out: “When we started, it soon became apparent that it is very difficult to find out what the basic requirements are. There is no ‘how-to’ guide for that [Article 11.13]. And that was of course also because Article 11.13 did exist, but had never been used before.” As a result, many initiatives were obliged to conceive their own standards at the start of the process, with some using as a guideline the legal standard set by the UK government. However, as the urgency of the crisis declined, quality requirements became clearer and stricter again.

Yet, even when a prototype is developed, there are more hurdles to overcome before certification is awarded and production can begin. This

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5 CE stands for E stands for “Conformité Européenne”, the French for European conformity. The CE mark means that the manufacturer takes responsibility for the compliance of a product with all applicable European health, safety, performance and environmental requirements.
needed so urgently innovations are needed and therefore whether to continue, freeze, or stop a marathon: **–**

- **Key findings of case studies.**

| Company          | Relevant information                                                                                     | Purpose                                                                 |
|------------------|----------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Demcon (based on proprietary product) | Obtaining an advanced market commitment for 500 pieces from the Ministry of Health triggered Demcon to start the product development process. The access to experts in hospitals accelerated the progress as it helped to adjust the design to the needs. Due to the urgency, lots of suppliers, including unfamiliar ones, offered their help. | Demcon was the first initiative to go through all the development steps and reach TRL 9. Demcon shared its experience and contacts with the other initiatives during the joint work sessions. This included knowledge on the critical innovation steps, the certification process and the business case. |
| Freebreathing (based on MIT e-vent) | A strong collaboration between a company and a University Medical Center provided a knowledge base for the development of the ventilator. Collaboration with two production companies and a software development company accelerated the development of the innovation. | While lagging in the TRL of their product development, Freebreathing quickly learned from the shared experiences of initiatives such as Demcon and Operation Air to build a different business case for its product. |
| Operation Air (based on Philips design) | Collaboration with and support from other other productive parties even offered to stop their own production process to produce components for us”. | Project Operation Air was the second initiative to go through all the development steps and reach TRL 9 – after Demcon. Project Operation Air shared its manual for accelerated certification with the other initiatives during the work sessions. Project Operation Air decided not to develop for international countries after realising through the work sessions that the international environments would not support their products. |
| Project Inspiration (based on historical product) | The initiative was started after it got into contact with the museum of science and medicine to borrow an old ventilator. The initiative could build on contacts with medical experts, an organization that develops electronic equipment, and a consulting firm that offered practical support. | Project Inspiration was late to join the initiatives. It maintained regular contact with the other TU Delft initiative (Project Operation Air) and learned from its experiences. |
| Dirty Boots (based on MIT e-vent) | Dirty Boots was approached by Hospitalier to develop a ventilator for their medical emergency containers. Phonecalls with a medical expert was of value to the ventilator design. There was an international network of contacts (also on ministerial level). | Via Hospitalier, Dirty Boots was in contact with international parties. Those involvements revealed that it was not easy to identify the requirements in other countries, especially third world countries. Dirty Boots shared their experiences on international contexts in the work sessions. |
| Neitrac (based on MIT e-vent) | Collaboration with support from other other companies has been considered a success factor in the process. | Neitrac found it helpful to get into contact with the other initiatives. This was a confirmation of dealing with a serious issue and challenge. The exchanged knowledge made this initiative decide not to proceed with the development of their product. |
| Open Air (based on MIT e-vent) | The collaboration and knowledge exchange with other initiatives and experts was found interesting and useful. The experiences shared made this initiative decide not to proceed with the certification of their product. | The collaboration and knowledge exchange with other initiatives and experts was found interesting and useful. The experiences shared made this initiative decide not to proceed with the certification of their product. |

... gives the initiatives the feeling that what started as a sprint is becoming a marathon: “You make a sprint, and quick results give new energy: but at a certain point it turns out that you are running a marathon” (Interview with Project Inspiration). At this point—when solutions are not needed so urgently—initiatives start to reconsider how badly their innovations are needed and therefore whether to continue, freeze, or stop production altogether as they consider whether there will be a market for their product once the crisis window of opportunity has closed. In other words, as long as the level of infections and deaths is creating an urgent need for alternative ventilators, there is a momentum for the development of alternative product offerings, which must accommodate both technical requirements and user needs. Once...
measures to counter the spread of the virus in the Netherlands start to take effect, demand for the ventilators will drop and the standards required for quality certification will rise again. Consequently, there is momentum to develop alternative designs for only several weeks. The lesson here is that the window of opportunity during a crisis is determined by urgency and has a timeframe associated with that urgency. Skipping steps in the innovation process does not save time.

4.2. Collaboration during the COVID-19 crisis

The development of alternative ventilators is a complex technological process with a clear link to society as its main users are nurses and hospital specialists. Most of the initiatives, however, started developing their alternative ventilators with a focus on core technologies, including for instance the regulation of respiratory rate, inhale/exhale volume, monitoring (software), and more. While this focus on technology enables the innovators to develop prototypes rapidly, it also risks neglecting—or overlooking altogether—important societal dimensions. Although designing alternative ventilators may seem easy in theory (i.e., it must deliver oxygen to a patient who cannot breathe unaided), in practice it is more complex because the design must cater for not only the preferences of medical personnel but also the existing hospital environment and the range of patients to whom they will be fitted. Furthermore, suppliers play an important role in providing the crucial components for the alternative ventilators, components which may be scarce during crises. During the innovation processes, for example, there was a worldwide shortage of the materials necessary for the development and production of respiratory equipment because factories were closed, trade was reduced, and there were new import and export regulations to comply with: “Suppliers were closed, parts were not available and factories in Italy were closed. We had ordered tools, but they weren’t there two weeks later. [They] turned out to be stuck at customs at the border of Poland” (Interview Dirty Boots). Here, collaboration appears to be crucial for innovation processes to overcome these challenges.

First, we consider interdisciplinary collaboration, where the initiatives involved technical, medical, and legal experts in the innovation process as well as relevant bodies, stakeholders, suppliers, and end users (see Table 3). With such interdisciplinary collaboration, initiatives can exploit knowledge and resources from a broad range of domains, sectors, and markets to scale up. Freebreathing’s experience is illustrative: “From a technical point of view it was a good team, [but] not from a commercial point of view. [We are] not in the medical market. In that sense, it was a good team, per se” (Interview Freebreathing). This is why Freebreathing started its innovation process in close collaboration with ICU doctors at a Dutch hospital. As a result, its innovation process was relatively smooth because it accommodated medical demands from the start.

Involving diverse disciplines and experts in the development process therefore seems necessary if an innovator wants to bring a new product to market before the crisis window of opportunity closes. Such collaborations stimulate openness and cross-overs between actors, and mobilize knowledge and resources from various domains, sectors and markets that can spur the development of alternative ventilators. The important lesson here is that the window of opportunity during a crisis is short, and interdisciplinary collaboration can spur innovation processes.

4.3. Collaboration between the initiatives during the COVID-19 crisis

We set up this study around the time of the first peak of the COVID-19 pandemic (March 2020) with the specific aim to help the various initiatives develop their alternative ventilators faster. Our needs analysis produced a list of challenges for which the initiatives needed input, knowledge, or resources beyond those already acquired or available from their collaborators. We organized interdisciplinary joint work sessions to facilitate the exchange of technological, medical, legal, and international expertise between experts and all of the initiatives for alternative ventilators in the Netherlands. There was enthusiasm throughout the six-week period to participate in these interactive work sessions, which enabled the initiatives to address a common societal goal (rather than company goals per se) in finding ways to meet demand for medical ventilators. Moreover, the joint work sessions represented a forum in which all participants could share their knowledge, experience, and contacts so that the other initiatives could learn from it and accelerate their innovation processes: “Our experience with developing and producing the AirOne has taught us a lot, and we are happy to share this experience with others, with the aim of fighting against this virus. […] As experts by experience, we are happy to share our lessons learned in order to accelerate the production of alternative ventilators elsewhere” (Interview Operation Air).

Such nested collaboration - in which (collaborative) initiatives engage in open collaboration with other (collaborative) initiatives to address the challenge at hand - facilitates the learning process in addressing a specific problem. For example, initiatives that had already started the certification or the production process were able to share their experience with initiatives who were just starting out. As a result, initiatives gained new knowledge, insights and contacts that could be used to accelerate their respective innovation development. The
important lesson here is therefore that the innovation process during crises can be accelerated when actors collaborate non-competitively with other initiatives in nested collaboration settings.

4.4. The intermediating role of purpose

For most initiatives, the rapid spread of the coronavirus represented a key motivator to develop alternative ventilators and help avoid the situations seen in, for instance, China and Italy: Lives are at stake. So, the need to find solutions right now represents one of the biggest challenges: “In the back of your mind, you think the entire time: If we don’t hurry, people will die. That feels quite different from not meeting a deadline” (Interview Dirty Boots).

That same sense of urgency also creates a sense of purpose and benevolence (see also Table 3). For instance, all initiatives were willing to work overtime, and major suppliers and stakeholders were willing to invest. There was also widespread willingness to volunteer or to supply materials quickly and at cost price. Indeed, many initiatives received donations and philanthropic contributions. Media attention, visits from senior officials, and positive responses from society further encouraged such developments, heightening the feeling of making a contribution to society. Purpose is therefore important to accelerate the innovation process.

However, purpose also functions as an intermediating factor for collaboration to accelerate the innovation process during crises. For example, in our study we noted how each of the initiatives mobilized a large community of volunteers keen to contribute to the development process without expectations of any monetary gains. Furthermore, during the joint work sessions, initiatives were happy to collaborate with other initiatives with no expectation of financial gain. Rather, the goal of finding a solution right now and making a difference in the fight against COVID-19 was the central purpose. Here, the important lesson is that purpose plays an important intermediating role in accelerated innovation processes during crises.

5. Discussion

This study has illuminated the need for accelerated innovation processes during crises and emphasized the role of collaboration in such processes. In this study we have considered the development of alternative ventilators to treat COVID-19 patients in the Netherlands.

Our results indicate that the COVID-19 pandemic creates what we introduce as a crisis window of opportunity for the development of alternative (in this case medical) products. The more acknowledged concept window of opportunity relates to research around entry-timing advantages. After initial discussions on pioneering advantages for firms (see e.g. Refs. [70–72], extant research generally associates high firm performance with entry during a window of opportunity that occurs between the emergence of a dominant category [73] and the emergence of a dominant design [31,33,48,74]. We illustrate the existence of a crisis window of opportunity that emerges only in crises or emergencies (i.e., wars, economic downturns, natural disasters, or pandemics). This window can emerge in mature industries where a dominant category and design has been established as the crisis challenges dominant designs based on newly emerging needs and requirements. The crisis window of opportunity is inherently bound to the urgency of the crisis at hand, meaning that as soon as the crisis is resolved or is under control, the window closes. This urgency is an important trigger for accelerated innovation processes.

Following extant research, our results also indicate that collaboration plays an important role in enabling such innovation processes during the crisis window of opportunity, as the knowledge and resources that initiatives lack can be brought in to develop innovative products. More importantly, our results indicate that nested collaboration can enable accelerated innovation processes as a forum for coordinated knowledge and resource exchange between the initiatives is created, increasing the potential for learning and coordinate knowledge and resource exchange. Differences in the status quo of the respective initiatives further increase the learning potential and accelerate the innovation process.

We also highlight the intermediating role of purpose in accelerating the innovation process, which provides the incentive to set aside any competitive advantage or monetary benefit in favor of finding a solution and making a difference right now.

5.1. Implications

Our study provides interesting new perspectives on accelerated innovation during crises, meeting calls for such studies (see e.g., Refs. [17,20]. We will discuss three important theoretical implications. First, we contribute to the emerging literature on accelerated innovation processes (see Ref. [11], with a specific focus on such processes during crisis situations). Our study indicates that, in line with previous studies (e.g. Refs. [8,10,55], skipping important innovation development
steps—such as the identification of user needs or certification requirements—to compress activities into a shortened timeframe is detrimental and does not produce any time gains. To avoid the “speed trap” that is so detrimental to accelerated innovation processes (see Ref. [10], our findings indicate that nested collaboration can accelerate innovation processes, despite the time it takes to establish relationships (see [26, 27, 29, 30]). That is, while interdisciplinarity collaboration within an initiative enables the sharing of knowledge and resources necessary to develop a new product, non-competitive nested collaboration among initiatives in joint work sessions provides access not only to additional knowledge and resources but also to new contacts and NPD experience. As such, nested collaboration accelerates innovation processes. Our results show that studying innovation processes outside traditional organizational contexts and timeframes enables us to defy existing studies, which have repeatedly found that time pressure is detrimental for innovation processes [8, 10], and highlight ways in which acceleration can be achieved when needed.

Second, our findings contribute to research on collaboration and open R&D. Research has already indicated the various ways that innovation can happen across boundaries during crises (see e.g., Refs. [3, 14, 17, 24]). Similarly, our findings illustrate how encompassing interdisciplinary experts can help initiatives in their innovation efforts. That is, all of the initiatives we analyzed were able to connect to a diverse set of stakeholders, with different backgrounds, expertise, and resources, that enabled the development of the alternative ventilators. We contribute to this line of research a new collaborative organizational form—nested collaboration—which has supported the acceleration of innovation processes during the COVID-19 crisis. Nested collaboration happens when initiatives openly collaborate with other initiatives to address a specific problem. Those nested collaborations enable these initiatives, often at different stages of development, to share knowledge and experiences that could aid the other initiatives in their development, despite being at different stages of development or working at a different pace. As a result, nested collaboration provides an important way to dismantle knowledge boundaries between initiatives and enable crowdsourcing among initiatives, which could accelerate innovation to address crisis-generated problems such as those related to COVID-19. Our nested collaboration model represents an important, valuable, and novel crowdsourcing contribution to the literature on collaboration in addressing problems or challenges [11, 14, 17, 24, 42] and deserves further exploration.

Finally, our research contributes to the acceleration and collaboration literatures as well as the crisis and innovation management literatures (see Refs. [20, 36, 39]) by highlighting the importance of purpose in accelerating innovation processes. That is, the COVID-19 crisis spurs feelings of engagement and the willingness to contribute. Next, we find that purpose provides an important intermediating mechanism that could enable collaboration to accelerate the innovation process. That is, the purpose of finding a solution enables initiatives to willingly share resources, knowledge, experiences, and contacts without expectation of monetary gain or competitive advantage. Moreover, the purpose of finding a solution can spur alternative, philanthropic financial support for innovations that address problems generated by the crisis. In short, to tackle a crisis-generated problem [37] or grand societal challenge [75] effectively, it is important to create a community (comprising individuals, initiatives, and collectives) with a common purpose of innovating to address a given problem. We therefore define innovation during the COVID-19 crisis as purpose driven and initiated with the sole purpose of quickly finding a solution to an urgent societal challenge.

Our results have two important caveats. First, innovation is linked directly to the urgency to find solutions to the problem (i.e., a pandemic). As soon as the urgency decreases (i.e., when, due to government restrictions, the spread of the virus slows down), the need for alternative products also decreases. For managers and product developers, it is therefore important to consider the market value of their alternative products beyond the crisis window of opportunity. For instance, even after the COVID-19 pandemic, there might still be demand for a mechanical rather than a manual ventilator based upon the Ambu-bag®. Second, given the sense of purpose and that many firms want to find solutions to the challenge at hand, the crisis window of opportunity can become overpopulated. As outcomes from innovation, R&D activities, and investments are uncertain [36], it is important therefore to consider how best to support these multiple R&D contributors during a crisis. In the Netherlands, policies such as advanced market commitments and targeted research subsidies based on ex ante value have been used to support a limited number of initiatives early in the innovation process. Our study suggests, however, that joint research funding to enable nested collaboration might provide an important additional policy instrument that has to date been overlooked in the Netherlands. After all, it was during the joint work sessions that most initiatives gained crucial information, knowledge, experience, and contacts from one another that influenced the pace of their developments in this unprecedented time. As such, policies should be designed to encourage and direct innovation processes during a crisis when even the slightest acceleration of innovation might bring significant benefits. Our findings present important avenues for future research to investigate accelerated innovation in response to crises or other grand societal challenges.

5.2. Limitations of this study and suggestions for future research

The acceleration of innovation by building on collaborative models provides valuable insights into the fight against COVID-19. We argue that our findings, albeit specific to COVID-19, may be generalizable, and not solely to health-based crises. More specifically, our findings constitute a relevant starting point for studying accelerated innovation processes in other emerging crises characterized by the need to act urgently but at the same time with long-term impact. There is a need for more research into the identified concepts and relations regarding the role of collaboration, purpose, and time during such crisis situations.

An important next step is to compare real-time data and research findings from this crisis with data and research findings after the crisis, which would ideally include data from people so deeply involved in crisis management that they were originally unavailable. In our study this would include, for instance, interviews with various people involved in the accelerated certification process or policymakers from the Ministry of Health, Welfare and Sport. We argue that these informants, together with reflections on the innovation process and assessments of any long-term impact, might provide additional input to help us better understand accelerated innovation processes during crises and how they might be sustained and/or evolve after the immediate crisis to enable long-term impact.

5.3. Conclusion

In the context of the COVID-19 pandemic, this study highlights the need to investigate new ways of leveraging our ability to innovate quickly when the need is high and the time is limited. In conducting this study we have been truly impressed by the determination of different actors to make a difference, and stunned by what can be achieved in just a matter of weeks. We hope this study inspires follow-up research to identify how innovation processes to address other important missions, goals, or societal challenges can be accelerated.

Credit author statement

Amber Geurts: Conceptualization, Data curation, Writing – original draft, Methodology, Investigation, Formal analysis, Supervision. Tara Geerink: Conceptualization, Funding acquisition, Data curation, Writing- Reviewing and Editing, Visualization, Supervision, Validation. Marit Sprenkeling: Writing-Reviewing and Editing, Methodology, Data curation, Visualization, Investigation, Formal analysis.
Declaration of competing interest
The authors have no conflicts of interest to declare.

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