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Research paper

"Can we build it? Yes, we can!" complexities of resource re-deployment to fight pandemic.

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ABSTRACT

During the COVID-19 pandemic, several countries asked their domestic firms to produce various medical equipment. Many firms promised to do so, including redesigns of existing ventilators or designing new ones. Despite these firms' enthusiasm, however, many of their attempts at being *resourceful-* through deploying their resources in activities beyond their current use- were unsuccessful. Our study attempts to explain why the success of these efforts varied. We integrate concepts of resourcefulness, managerial cognition, and product architecture to develop a typology of resourcing approaches, using a firm's characteristics and resources, its interpretative frames, and the technical and regulatory characteristics of the product being resourced for as boundary conditions. We illustrate our theorizing through case studies on the manufacturing of face shields, hand sanitiser, face masks, and medical ventilators. Our study provides important implications for firms attempting to deploy their resources in new contexts.

"Eric Humphreys began building a DIY breathing machine. "I literally used Christmas parts," he says. But he and his boss, Manu Sawkar, the founder of Standard Transmission, also realised that this "DIY MacGyver creation," as Sawkar puts it, wasn't even vaguely ready for prime time. Real ventilators require considerable testing for reliability. They have to monitor patients and set off alarms if too much or too little air is going to the lungs. They have sophisticated algorithms to regulate flow depending on how well the patient is inhaling. Even if Standard Transmission did create something usable, Sawkar says, it would never be able to manufacture enough units to interest the city. So Humphreys's creation will go no farther than a well-meaning gesture." (Levy, 2020)

1. Introduction

As COVID-19 became increasingly widespread, governments worldwide realised their healthcare systems risked being overwhelmed. Most countries lacked adequate hospital capacity, ICU units, ventilators, and personal protective equipment (PPE). In the UK, for example, early estimates suggested that the NHS would be short of 20,000 ventilators (Davies & Rankin, 2020). In response, several governments called on private-sector firms to help produce PPE and ventilators.[1] Many organisations, including LVMH, Airbus, Dyson, GM, and Ford, offered to deploy their resources, some individually and others jointly, to produce the needed items, including hand sanitiser, face shields or simple fabric face masks, medical-grade face masks,[2] and ventilators. These efforts were supported by individuals and organisations sharing relevant information, designs, and design blueprints (Chesbrough, 2020; Crick & Crick, 2020) and by relaxing some requirements and rules about producing these goods. Many attempts at being *resourceful-* through deploying resources in activities beyond their current use- were, however, unsuccessful or deficient: some products were of unacceptable quality, could not be produced at scale, had limited clinical effectiveness (e.g., only short emergency use), or failed to secure regulatory clearance.[3] It is crucial that we understand *why some initiatives succeeded while*

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[1] In some cases, such as the United States or Taiwan, national governments also invoked various requisitioning acts, thus obliging some organisations to take part in the efforts.

[2] We use the term medical face masks referring to masks that are approved for use in hospital setting and are made with specialist non-woven material and electrostatically charged. These include both the loose-fitting face masks (sometimes referred to as surgical masks) and close-fitting N95 respirators.

[3] We define successful initiatives as those that led to products that were safe, effective for the intended use, and could be produced at scale.

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others failed.

We address these questions by integrating the concepts of resourcefulness and resourcing (Baker & Nelson, 2005; Korsgaard, Anderson, & Gaddefors, 2016; Sonenshein, 2015) with literature on innovation types (Henderson & Clark, 1990; (McDermott & O'Connor, 2002; Tushman, Smith, Wood, Westerman, & O'Reilly, 2010). Resourcefulness denotes an ability to redeploy existing resources in novel ways to address an issue or create a new opportunity (Baker & Nelson, 2005; Korsgaard et al., 2016; Sonenshein, 2014). It explains how relationships among existing objects (or capabilities) that are redeployed, interpretive frames, and environmental limitations influence success. But its boundary conditions are not well understood (Williams et al., 2019). The innovation literature suggests product complexity is one boundary condition: for product development to succeed, product characteristics such as architecture (Henderson & Clark, 1990), number of components, and regulatory specifications (De Toni et al., 1998; Hobday, 1998) require different knowledge types and actions (Henderson & Clark, 1990). Therefore, we argue that the success of firms' attempts to apply their resources and capabilities (Sonenshein, 2014) during the pandemic depended on the suitability of their resourcing approaches, the interpretative frames used to enact their resources, the characteristics of the product resourced (Weiss, Hoegl, & Gibbert, 2013), and, in some cases, relevant institutional support or governmental intervention (Hung, 2002). We start by proposing a theoretical framework that proposes *successful resourcing* is based on the relations among three dimensions: 1) objects- which are tangible and intangible assets that a firm owns or can access; 2) interpretative frames- which are constituted by firm's knowledge and provide the frames through which alternative uses of objects can be envisioned; and 3) product architecture- which refers to the characteristics of the product for which resourcing is directed. Based on this framework, we propose a typology of resourcing approaches that focuses on the relations among these dimensions. We also argue that when resource redeployment is too difficult for one firm because of a product's architecture, coordination among firms is necessary. We illustrate our framework by analysing case studies of recent resourcing initiatives for face shields, hand sanitiser, medical face masks, and medical ventilators. We selected these categories to reflect the implications of increasing architectural complexity.

Our paper makes several theoretical and practical contributions. First, we contribute to the strategy literature by integrating the resourcefulness and resourcing theory with the literature on innovation types. Our framework proposes boundary conditions for the resourcefulness concept by suggesting how different resourcing approaches and actions are more appropriate in certain contexts. Second, our findings suggest that resourcefulness for architecturally complex product categories might require coordination by policy makers and collaborative innovation. Practically, our proposed framework can help managers who must assess a priori how feasible their innovation initiatives are. This framework can help prevent firms from pursuing unrealistic or unnecessary goals. For example, Dyson spent around £20 million to develop a ventilator that the UK government rejected. Our findings also offer useful advice for practitioners who must mobilise and manage industrial collaboration. Thus, our paper augments the current discourse in industrial marketing management on how resources can be redeployed, shared, or combined (Chesbrough, 2020; Crick & Crick, 2020) and can thus reshape or open new market opportunities (Möller, Nenonen, & Storbacka, 2020). It also adds a perspective on managing through crisis (Pedersen et al., 2020). Finally, we see the paper as suitable for teaching strategic innovation management.

In this paper, we first briefly review the resourcefulness and resourcing perspective and the innovation types literature, and we use these concepts to present our tripartite integrative framework. We then illustrate our theorizing through three case vignettes. Finally, we discuss our findings and develop theoretical and practical implications.

2. Resourcing theory: Differentiating between "objects" and "resources in use"

The concept of resourcefulness is central in the entrepreneurship, innovation, and strategy literatures (Clough, Fang, Vissa, & Wu, 2019; Deken, Berends, Gemser, & Lauche, 2018; Feldman & Worline, 2011; Senyard et al., 2014; Wiedner, Barrett, & Oborn, 2017). Firms exhibit varying levels of resourcefulness- which we define as a firm's ability to bring, create, combine, and/or deploy existing or new resources to seize and respond to opportunities (Baker & Nelson, 2005; Korsgaard et al., 2016; Sonenshein, 2014). Resources have a "multitude of potential uses" (Korsgaard et al., 2016: 187) that are limited by managers' imaginations and their interpretative frames (Penrose, 1959). This concept applies both to resource-constrained firms that must make do with what they got through bricolage (Baker & Nelson, 2005; Welter et al., 2016) and to resource-rich firms that envision better alternative uses of their resources (Sonenshein, 2014).

Unlike early accounts of the resource-based view (RBV), which focused on resources' innate qualities as determinants of firm's performance, the resourcing perspective shifts the attention to the process through which "resources gain their strategic value" (Deken et al., 2018: 1923). Early RBV perspectives (Barney, 1991; Barney, Ketchen Jr, & Wright, 2011) examined how the innate qualities of physical, human, and organisational assets (Eisenhardt & Martin, 2000) – or, as referred to in resourcing perspective 'objects' - can enable a firm to realise its strategy. This perspective does not, however, explain how assets become valuable (Schneider, Bullinger, & Brandl, 2020) or what the boundary conditions of an object being a valuable resource are. To explain this process, the resourcing perspective examines how practitioners enact assets in practice. It argues that assets become resources only when "organizational members take up and use assets as they pursue activities in line with what they wish to make happen in the world" (Feldman & Worline, 2011: 630).

Resourcing theory distinguishes between an "object", which can be a tangible or an intangible asset and a "resource", which is an object that has already been *acted on* to offer value (Feldman & Worline, 2011). In this perspective, an object is defined broadly and can include various forms of knowledge and relational ties like a business ecosystem or supply chain relationships. Such knowledge or ties become resources only when they are deployed to create value, and their potential to become resources is shaped by actors' interpretative frames of how they can be used. That is, "the designation of resource is not just about the innate qualities of a material or nonmaterial asset, but about the nature of the relationship between the asset and what it helps to create" (Feldman & Worline, 2011: 631). As Feldman and Worline (2011) argue, breadcrumbs, as an object, becomes a resource when used to enact the meatball framework. In contrast, although pellets of metal could be used to enlarge meatballs, this would be inconsistent with the framework of meatballs as being edible. Similarly, resourceful enacting of meatballs with horse meat was deemed as beyond social and legal frameworks (Higgins & Castle, 2013). Thus, the limits to resourcefulness are dictated by shared interpretative frames, which reflect physical, legal, and social rules.

Nonetheless, we still know little about the boundary conditions of successful resourcing. What roles are played by interpretative frames and the characteristics of the product that is being resourced for? For example, why could some firms successfully redeploy their resources in

the effort to fight the COVID-19 pandemic, while others failed?

2.1. Interpretative frames

Recently, strategy scholars have suggested that managerial cognition and mental models are the micro-foundations of dynamic capabilities (Eggers & Kaplan, 2013; Felin, Foss, & Ployhart, 2015; Maitland & Sammartino, 2015; Salvato & Vassolo, 2018). This shift recognizes that managers develop and deploy organisational resources and capabilities while relying on mental models, which are "simplified representations of the world in order to process information (Simon, 1955)" (Tripsas & Gavetti, 2000: 1148). Those interpretative frames (sometimes referred to as schema, schemata, or cognitive frames)[4] therefore shape managers' cognition by i) focusing their attention on certain dimensions of the environment (Kaplan, 2008) and ii) providing them with assumptions about how the world works (Weick, 1995).

While interpretive frames can facilitate decision-making by leveraging previous experience, they can also lead to competency traps, in which individuals become strongly committed to a certain frame that keeps them from considering alternative interpretations and leads to sensemaking failures (Tripsas & Gavetti, 2000; Weick, 1995). Over-reliance on pre-existing frames can be problematic during unprecedented circumstances "that require inferential flexibility and alternative conceptualizations" (Cornelissen & Werner, 2014: 190). As Benner and Tripsas (2012) argue, such rigidity can occur when individuals analogically extend frames from their existing industry to an emerging one. Although analogical reasoning can be an effective way to transfer a solution across contexts, its success depends on how accurately actors conceptualise the differences between their base domain and the new target domain (Gentner, 1983). For similar contexts, actors with prior knowledge in these domains are more likely to use analogical reasoning successfully and effectively redeploy capabilities in new contexts (Gavetti, Levinthal, & Rivkin, 2005; Mastrogiorgio & Gilsing, 2016). Nonetheless, actors can overemphasize superficial similarities between contexts while ignoring critical differences (Cornelissen & Werner, 2014; Lovallo, Clarke, & Camerer, 2012), including regulatory or technical aspects of the product that are obscured by the apparent similarities between contexts. For instance, food companies that attempted to enter nutraceutical markets and pharmaceutical companies that attempted to enter food markets failed for this reason (Siedlok, Smart, & Gupta, 2010). As we argue below, the interpretation of a product is also affected by its architecture and the regulatory roles that govern its design specifications.

2.2. Product architecture: What is being resourced?

A product architecture consists of the 1) the arrangement of its functional elements, which denote what the product does; 2) the mapping of functional elements to physical components, or which component accomplishes what function(s); and 3) the interfaces among the physical components (Ulrich, 1995). Ulrich (1995) distinguished between integral and modular product architectures, which exhibit differing levels of interdependence among components and interfaces. Modular architectures exhibit a one-to-one mapping between the product's physical components and its functional elements and a system of decoupled interfaces (Brusoni & Prencipe, 2001; Ulrich, 1995). Components in modular architectures can be easily changed and produced by different firms (Sanchez, 2008). This characteristic increases flexibility, makes it easier to upgrade components, and enables firms to offer a variety of products (Sanchez, 2008). In contrast, integral architectures involve a "complex mapping between physical components and functional elements and coupled interfaces between components" (Brusoni & Prencipe, 2001: 182). The high interdependence among components and the tightly coupled nature of interfaces mean that a change in one component has cascading effects on the product architecture (Burton, Nyuur, Amankwah-Amoah, Sarpong, & O'Regan, 2020).

As the interdependence and interactions among a product's physical components increase (Mastrogiorgio & Gilsing, 2016), product complexity usually follows. Integral product architectures are a hallmark of high-end products (e.g., iPhone, Hard Disk Drives) and often rely on integrated supply chain architectures, with strong cross-company links that can create high entry barriers and limit the adaptive fit of a product or technology (Hung, 2002). This tight coupling limits the possibility of using alternative objects as subcomponents. As Dew, Sarasvathy, and Venkataraman (2004) argue, exaptation is more likely to take place in highly decomposable systems because the low interdependence among components allows actors to envision the use of different objects in the product design. Relatively high levels of decomposability usually lead to more expansive design options (Andriani & Carignani, 2014; Baldwin & Clark, 2000; Mastrogiorgio & Gilsing, 2016).

This tendency is relevant to our study, where some components of medical products are in short supply because of the pandemic. Some non-specialised firms attempted to make up for this shortfall by attempting to use their objects as substitutes. While this strategy might work in simple products like face shields, it is more likely to fail for complex products with high interdependence among subparts. It is also less likely to work for medical equipment, which is highly regulated with detailed specifications to ensure product quality and patient safety. Because firms need to obtain regulatory approval for their products, product architectures stabilise and relatively strict design rules emerge (Baldwin & Clark, 2000). These rules may facilitate technical understanding among players in the industry, but they can impede the "ability to fundamentally (re-)define and develop architectural innovations, since the considered problem-definition and solving space will be constrained by the mere presence of design rules" (Hofman, Halman, & Van Looy, 2016: 1437). Resourcing therefore requires some fuzziness in rules to provide actors with the necessary level of guidance while also allowing them a wider space of possibilities.[5] This fuzziness can be exploited by entrepreneurs who ignore established assumptions about the meaning of the technology or artefact, redeploying those in new contexts or new configurations (Gilbert-Saad, Siedlok, & McNaughton, 2018; Verganti & Öberg, 2013). Governments and regulatory agencies can be important in such instances because they can change design specifications to incentivise firms to resource for certain products. For example, to mobilise the private sector to produce ventilators, which can temporarily stabilise patients, the UK government introduced guidance in March 2020 on the minimal acceptable specifications for ventilators.

To summarize, we argue that the success of firms' attempts to be resourceful by redeploying their objects in novel ways depends on the interrelations among three dimensions: 1) objects- which refer to the tangible and intangible assets that a company owns or can access; 2) interpretative frames- which provide a framework for how objects can be used differently; and 3) product architecture- which refers to the technical and regulatory characteristics of the product that is being resourced for (see Fig. 1).

Firms might possess tangible assets such as equipment and production capacity or intangible assets such as specialised technical knowledge and well-established relationships within, or the knowledge required to coordinate, complex supply chains. Thus, we regard tacit knowledge as an object in this sense. These objects need to be enacted through interpretative frames, which guide actors about how to use

[4] We use the term 'interpretative frames' across the paper as a mean to simplify the argument and avoid lengthy deliberation on the related concepts of mental models, cognitive representations, mental schemata etc. (Eggers & Kaplan, 2013)

[5] For simplicity, we refer to this set of rules as institutional fuzziness.

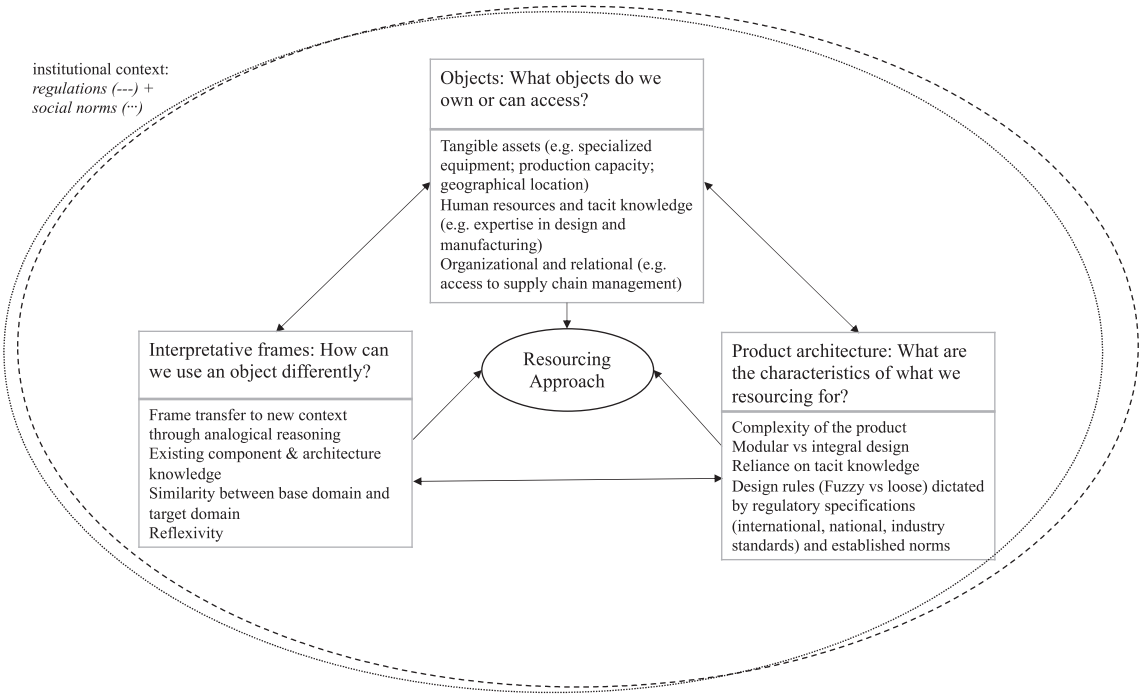

Fig. 1. Theoretical framework for resourcing strategy.

these objects in new contexts. Successful transfer of objects to new contexts will therefore depend on the validity of the frames used to map the similarities between the base and target domain. The usefulness of these frames also depends on the technical and regulatory characteristics of the product that is being resourced for. When the product is simple and the target domain shares some similarities with the firm's base domain, managers might be able to analogically extend their frames and successfully redeploy their resources. However, analogical transfer in complex and uncertain situations is difficult (Gary, Wood, & Pillinger, 2012). In product categories with highly complex architecture, extending pre-existing frames to new contexts might be problematic; firms might overemphasize similarities and underestimate the complexity of the product (Schwenk, 1984) and hence fail to successfully redeploy their objects. In such situations, decision-makers might benefit from being more reflexive about the potential limits of their frames in new contexts (Gary et al., 2012; Hibbert, Siedlok, & Beech, 2016). Rather than going with "gut feelings", convergent thinking and involvement from a wider range of stakeholders might be required (Gilbert-Saad et al., 2018) to augment knowledge about the new context. This, in turn, might require coordination or prior experience of working with partners across knowledge domains (Siedlok, Hibbert, & Sillince, 2015). As shown in Fig. 1, this resourcing process is embedded in an institutional context that shapes the socially accepted meaning of objects and the scope for extending interpretative frames across domains. Industry regulations and product specifications can also enable or restrict the scope for resourcing products. For example, by altering regulations or norms like the approval process and requirements for medical devices, changes in the institutional context can expand or narrow how an object is perceived and can be deployed.

We argue that the success of firms' initiatives during the pandemic reflects the interrelations among objects, interpretative frames, product architecture, and the institutional context in which they are embedded. Differently configured initiatives may require different resourcing approaches. We next present our research methods and illustrate our theorizing through several vignettes of different product categories.

3. Methodology

We aim to develop a theoretical explanation of successful resource deployment in new contexts through abductive reasoning, in which our theoretical framework is modified and refined by confronting it with the empirical world (Andersen & Kragh, 2010; Dubois & Gibbert, 2010). Case study approaches are particularly suitable for studying complex industrial marketing phenomena (Easton, 2010) such as resource redeployment in a naturalistic setting, where the boundaries between the context and phenomena are blurred (Dubois & Gibbert, 2010; Stake, 1995). As such, a multiple case study approach was deemed suitable due to its ability to build, extend, and refine theory (Eisenhardt, 1989; Graebner, Martin, & Roundy, 2012) and "to capture relevant features of a case through a particular framework" (Dubois & Gibbert, 2010: 131). The use of case studies therefore has an *illustrative* function (Graebner et al., 2012), which allows researchers to argue the validity of their theoretical propositions through real-life examples (see Finch & Geiger, 2011). Case studies also allow us to capture the similarities and differences in resourcing strategies across initiatives in different product categories (Elsahn, Callagher, Husted, Korber, & Siedlok, 2020) to assess *how* and *why* some organisations successfully deployed their resources in new contexts, while others failed (Eisenhardt, 1989; Lindgreen et al., 2010).

3.1. Case selection

Our case selection was theoretical (Eisenhardt, 1989) and emergent. As Fletcher & Plakoyiannaki (2011: 173) argue, "the definition of the unit of analysis is the fundamental answer to the question 'what to select'". Our unit of analysis is the initiative undertaken by an

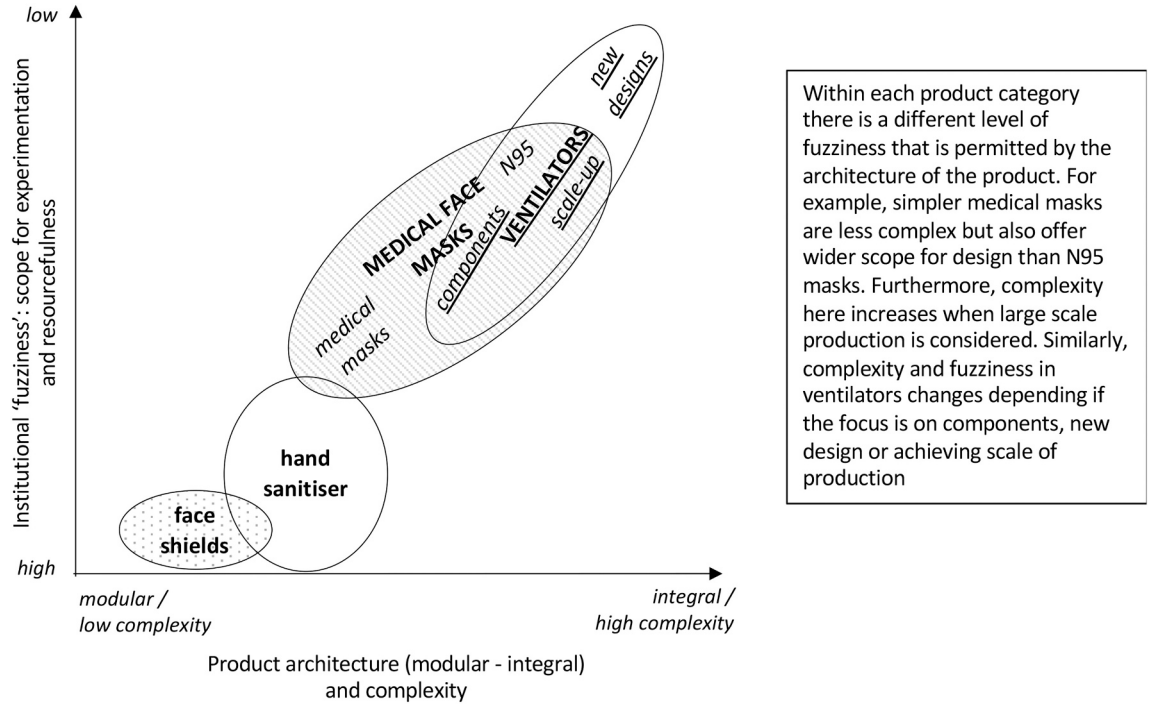

Fig. 2. Case selection.

organisation or a group of organisations to produce medical products. The case selection was iterative; we adjusted constantly among data collection, analysis, and case selection (Lingens, Miehé, & Gassmann, 2020). We began by focusing on specific firms, but later extended our focus to include other organisations and consortia. As our research progressed, we realised the characteristics of the product being resourced for helped shape the organisations' resourcing strategies. Thus, we decided to focus on initiatives across different product categories characterised by different levels of complexity and fuzziness. We initially considered a broad selection of product categories, including cloth face masks; track & trace systems, and other categories of PPE, but we decided to focus on initiatives across four product categories: face shields, hand sanitiser; medical face masks, and medical ventilators. These categories provide enough variance for the analysis. Fig. 2 illustrates the product categories that we sampled the initiatives from.

Within these categories, we sampled multiple initiatives that differed to detect variance across the initiatives. For example, we included initiatives that involved organisations working individually or collaboratively. Furthermore, we ensured that our sample included variation for both failed (e.g., abandonment, unacceptable quality or miniscule quantity, failing to secure necessary regulatory clearance) and successful (e.g., the end result was safe, clinically effective, and could be manufactured in high volumes[6]) initiatives to avoid success bias and to capture different patterns across the cases (Elsahn et al., 2020). Table 1 includes a list of the initiatives that we sampled in our study. We consider further what constituted success in the discussion section.

3.2. Data collection

Our approach is similar to previous studies which relied on secondary data to develop an in-depth understanding of observed phenomena and to illustrate theorizing (e.g., Finch & Geiger, 2011; Hung, 2002; Ritala, Golnam, & Wegmann, 2014; Rusko, 2011). Several authors have argued that secondary data present an "unexploited and rich source of data that should be used when primary data is not available" (Ritala et al., 2014: 240; see Ambrosini, Bowman, & Collier, 2010; Cowton, 1998; Harris, 2001). Secondary data can be particularly useful for studying events such as the pandemic because they are heavily covered by the press and governmental agencies and offer an abundance of secondary data (Kummitha, 2020). In addition, especially in the cases of failed initiatives, secondary sources can be a better alternative to interviews that avoid access issues or retrospective rationalisation by managers (Cowton, 1998; Harris, 2001). To ensure the quality of our data, we relied on a variety of sources such as governmental reports and regulations on medical equipment, news articles by reputable media, company reports and press releases, and video interviews with managers and industry experts. We also focused on news articles that relied on interviews with company representatives and industry experts. In our search, we focused on the four product categories and the emerging approaches to resource redeployment within each product category. As Ritala et al., (2014) did, we provide illustrative quotes in our findings section to enhance the transparency of our analysis (Lindgreen, Di Benedetto, & Beverland, 2020) and to clearly connect data to our theorizing. Table 1 provides an overview of our data sources.

3.3. Data analysis

In analysing our data, we adopted an abductive approach, which involved iteration between theory and data (Dubois & Gibbert, 2010) whereby our theoretical framework evolved "*simultaneously* and *interactively* with empirical observation" (Dubois & Gibbert, 2010: 131, italics in original). Specifically, we followed the "*in vivo approach*" (Andersen & Kragh, 2010), in which we took resourcing theory as a starting point to frame our inquiry, while continuously combining other theoretical perspectives and refining our theoretical framework in light of our engagement with the empirical material (Andersen & Kragh, 2010). This approach to theory building involved interpolation, which helped us "extend and/or combine received theory with empirical

[6] The definition based on these three characteristics is adopted from one such initiative - CoVent – and is based on how one of the managers on the project defined a successful development of a ventilator. See https://www.med-technews.com/features/working-round-the-clock-developing-a-ventilator-to-fight-cov/.

Table 1
Overview of the data sources.

Product category	Sampled Initiatives	Number and type of secondary sources	Total
Face Shields	Apple initiative to manufacture face shields. Bauer, a sport equipment manufacturer, initiative to manufacture face shields. The makers community initiative to produce face shields through 3D printing.	11 articles from reputable news and magazines 2 company websites 1 industry association website	14
Hand sanitiser	LVMH initiative to produce hand sanitisers. Craft distilleries and breweries initiative to produce hand sanitisers.	11 articles from reputable news and magazines 5 government/official information reports 1 university website 1 news bulletin video	18
Surgical Masks	GM initiative to produce surgical masks. Taiwan's face mask team consortium initiative to produce surgical masks.	15 articles from reputable news and magazines 1 company website 1 industry association website 2 government / official information reports 3 news video bulletin/interviews	22
Ventilators	Dyson's initiative to produce ventilators. Tesla's initiative to produce ventilators. NASA's initiative to produce ventilators. "VentilatorchallengeUK" consortium initiative to manufacture ventilators. "Vermontilator" initiative to produce ventilators. GM and GE healthcare initiative to produce ventilators. Ford initiative to produce ventilators. Taiwan ventilator team consortium initiative to produce ventilators.	55 articles from reputable news and magazines 7 company/consortia websites 1 industry association website 2 government / official information reports	65
Cross-case / general sources		15 articles from reputable news and magazines	15
Total sources used in initial analysis			**134**
Additional sources included during the review process		34 articles from reputable news and magazines 5 company/consortia websites 3 podcasts 3 reportage movies	45
Total sources			**179**

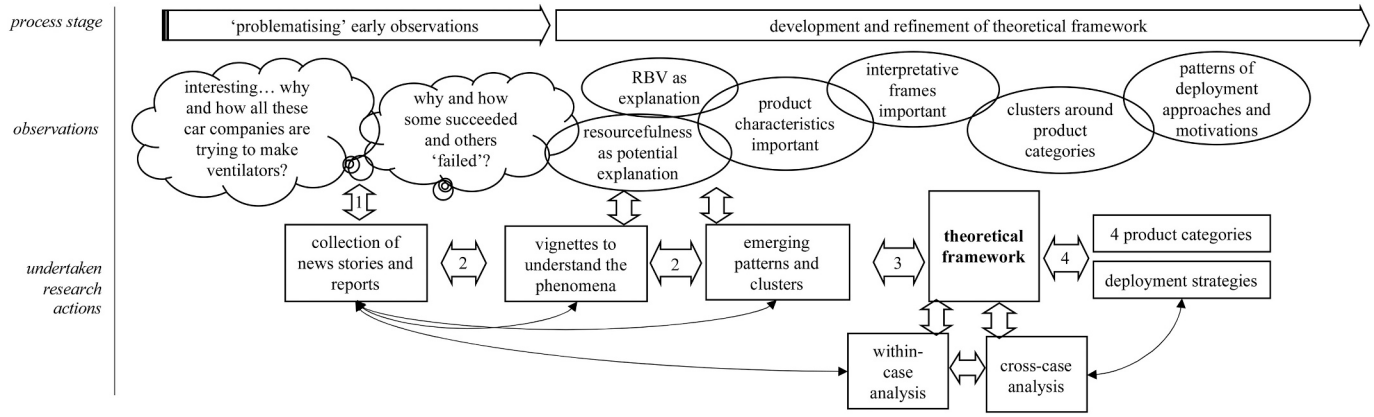

Fig. 3. Theorizing, data collection and data analysis: an iterative and abductive process.

findings and other theoretical perspectives in order to build new theory" (Andersen & Kragh, 2010: 51). As argued by Dubois and Gibbert (2010) the in vivo approach is particularly suitable to multiple case study design as the phenomena of interest is kept constant across cases while the theoretical framework evolves to make sense of similarities and differences between cases. It is difficult to describe all the iteration between theory and data. Retrospectively, we can identify four main stages in our data analysis: developing an understanding of each case through within-case analysis, refining and modifying our theoretical framework, cross-case analysis (Lindgreen et al., 2020), and aggregating themes and developing our final theoretical framework. Our data analysis process is depicted in Fig. 3.

Our inquiry started with the observation of firms attempting to deploy their existing objects in new contexts in the effort to fight the COVID-19 pandemic. By following several firms' initiatives, we noticed that many of these efforts were unsuccessful. To make sense of the variations in success, we turned to the resourcefulness and resourcing literature. This perspective provided an initial frame to make sense of the sampled cases through within-case analysis. We wrote a vignette for each initiative describing the resources (objects) used, the process, activities and overall deployment strategy, and the outcome. At this stage, we noticed that the characteristics of the product that was being resourced for and the actors' cognition and perception of the opportunity shaped the deployment strategy, and consequently its success.

Table 2
Main resourcing approaches.

Resourcing approaches	Characteristics of the core organisations
It's in our brand	High-profile organisations with access to complex supply chains, established clout (due to high visibility brand) and, potentially, leveraging their established brand in framing the resourced product. There seems to be a relation to the image of the company as being innovative (e.g. Tesla), design driven (e.g. Apple) and generally being proactive in bringing novel solutions or products on a regular basis, often with claims of helping consumers (cosmetic firms). The key factor underpinning the strategy being existing brand image.
We are already making it! Kind of…	Organisations that possess similar capabilities or already produce similar products, although sometimes operating in completely different markets (e.g. NASA, distilleries). The distance between home and target knowledge bases is generally small, though requiring analogical reasoning to make the connections between the existing and needed product or capability. Overall, these organisations, except for NASA, were often motivated by the opportunity to remain active and not needing to halt operations.
Eager helpers	Organisations or individuals that were intrinsically motivated, even if their resources and capabilities were not necessarily closely linked or fitting the requirements. There is a visible lack of assessment of the gap or consideration of other options of achieving the goal (e.g., partnering up), which often translated to reinventing the wheel or developing unnecessarily complex products or processes (e.g. 3D printing of face shields; focusing on developing new ventilator designs).
We are all in it TOGETHER	Organisations or individuals approaching the task in a more coordinated manner, leveraging different capabilities and resources across the partnership and recognising that collaboration is the only way to achieve the goals.
Not so eager helpers	Organisations or individuals that were in a position (e.g. existing mask producers), or deemed to be in a position (e.g. GM, Ford) to help by scaling up their efforts (which could be by partnering with others) or redeploying their resources (e.g. GM, Boeing), but lacked the same levels of intrinsic motivation to help. In those cases, governments utilised different mechanisms to either motivate them (e.g., payments tied to certain weekly production quota in Taiwan) or to compel them to act (e.g., GM). In most cases, these organisations were already involved in production efforts and fall into one of the other categories.

Therefore, we revisited our framework to incorporate insights from the cognition and product architecture literature to make sense of our observations. We developed our tripartite framework (Fig. 1), which is comprised of three dimensions: 1) objects- which are tangible and intangible assets that a firm own or can access; 2) interpretative frames- which are constituted by firm's knowledge and provide the frames through which alternative use of objects can be envisioned; 3) product architecture- which refers to the characteristics of the product to which resourcing is directed. We then revisited our cases and recoded them based on these dimensions. Subsequently, we engaged in cross-case analysis to identify the differences and similarities between initiatives to develop a theoretical explanation of the variations in success. We then identified five approaches to resourcing, as presented in Table 2. We developed these inductively by analysing all our cases and data. While doing so, we discussed similarities and looked for emerging patterns to resourcing. We paid attention to clues that highlighted motivation, challenges, and how organisations interpreted the products in relation to their existing capabilities.

Finally, we recorded new developments and news related to the four product categories and organisations that we focused on. Prompted by reviewers' comments, we reassessed our findings against new evidence and indicated the outcomes from a longer time perspective. This ongoing engagement allowed us to develop some additional insights related to the impact of these efforts after the initial goals were achieved. We highlight these in our discussion, along with limitations and future research. In the next section, we present our findings for the product categories that we studied, followed by a cross-case analysis in the discussion section to explicate our theoretical explanations (Piekkari, Plakoyiannaki, & Welch, 2010) and propose our typology of resource redeployment.

4. Redeployment of capabilities amid coronavirus pandemic

In this section, we provide illustrative cases accompanied by brief analyses in which we assess each product category from the perspective of the theoretical framework we propose in Fig. 1. We analyse product architecture, interpretative frames, and the object of resourcing. We inductively derived those from the data and used the three success criteria (safety, efficacy, and volume) to assess whether the approach succeeded. We then analysed the approach, and we note its risks and challenges.[7]

4.1. Face shields: Apple, sport equipment manufacturers and the maker community

Face shields are simple products that require little technical expertise and are not regulated in terms of design or manufacturing process. One manufacturer explained why so many firms attempted to produce shields: "shields need not be sterile, and "they're easiest to manufacture".[8] The interpretative frame of the product is generally agreed on: a piece of transparent material that protects the wearer's face from contamination, with relatively fuzzy design rules allowing for a range of design options or manufacturing approaches, without affecting performance. In Table 3, we analyse Apple, which had never produced face shields, Bauer, a sport equipment manufacturer that already had a similar product, and the maker community that mobilised to manufacture a range of equipment.

These cases illustrate the ease of frame transfer and deployment of resources. For Apple, these included monetary resources, access to and the ability to orchestrate supply chains, and some design capabilities. For Bauer, the challenge was to scale production with its existing equipment. The drivers are also different: for Apple it was a mix of philanthropy and marketing strategy while for Bauer a lifeline to stay open during the lockdown. The community of makers was driven by eagerness to help. Although, in this case rigid frames caused individuals to deploy resources inefficiently, as shown by their fixation on 3D printing when manual cutting was more effective. Thus, whereas Apple and Bauer succeeded, some in the maker community produced only miniscule volumes and overengineered the production process.

4.2. Hand sanitiser: Perfume makers and distilleries

Two main groups of companies tried to address the shortage of sanitiser: cosmetics / luxury brands such as LVMH and distilleries and breweries, ranging from multinational to craft producers. We analyse these two groups in Table 4. While sanitiser is not a complex product (80% ethanol, distilled water, hydrogen peroxide, and glycerine) and the basic recipe is publicly available on the WHO's website, its production is often regulated and requires a range of health and safety certifications. For breweries, it also required additional resources and competencies.

At LVMH, the production lines, skills and required materials for

[7] This is the part of analysis where we develop the five resourcing strategies proposed in Table 2.

[8] www.economist.com/united-states/2020/04/30/americas-makers-and-tinkerers-turn-their-hands-to-ppe

Table 3
Resourcing for Face Shields.

Product architecture	**Face shields:** (1) Very low product complexity. (2) Modular / simple component architecture. (3) No regulatory specifications for the product or the production process[1]. Manufacturing, expertise in safe machine use and design needed[2]. *Fuzzy design rules allow for a range of combinations, without affecting product performance. Lack of regulations allows for many simultaneous designs.*		
Example player (s)	**Apple:***It's in our brand*	**Bauer:***We are already making it! Kind of…*	**Maker communities:***Eager helpers*
Was it successful?	**Safe:***yes, easy to meet the criteria* **Effectiveness:***yes, easy to meet the criteria* **Volume:***yes, by leveraging supply chain management capability*	**Safe:***yes, easy to meet the criteria* **Effectiveness:***yes, easy to meet the criteria* **Volume:***yes, by leveraging existing manufacturing capability*	**Safe:***yes, easy to meet the criteria* **Effectiveness:***yes, easy to meet the criteria* **Volume:***no, small scale of production and often by adopting inefficient approaches fixated on existing technical capabilities*
Objects	Access to production facilities and materials, both internal and supply chain Supply chain management capability Design capabilities	Equipment and materials Knowledge of production process Spare capacity due to lockdown	3D printing equipment DIY capabilities Coordination and sharing of information via online platforms
Interpretative frames	(1) Familiarity with the component and architecture characteristics (2) Base domain of much higher sophistication in comparison to target base (3) *No need for analogical reasoning due to the simplicity of the product and the existing supply chain capabilities. For the design team this would be a low-level challenge*	(1) Perfect alignment of component with minimal change to architecture (2) Base domain required some modifications and learning (production process) (3) *Bauer displayed some levels of analogical reasoning to expand the frames of application for existing product. The process was aided by media coverage highlighting the demand and showing the design*	(1) Sufficient component and architecture knowledge of the product (2) Base domain needed some modification / development to apply existing knowledge (3) *Analogical reasoning was needed to match the available materials with the designs and production methods. The process was aided by knowledge sharing* via *online platforms*
Deployment strategy	*Challenges*: none *Risks / inefficiencies*: none *Approach:* Apple's position in the supply chain allowed it to muster the needed materials and production capabilities quickly and at scale. There was minimal challenge for the company as the components and the design are relatively simple. Additionally, Apple released detailed manufacturing instructions.	*Challenges:* scaling up production with existing machinery *Risks / inefficiencies*: none *Approach:* Existing product capabilities had a direct application with no requirement for new knowledge development or changes to the product. Existing capabilities allowed for limited production. Management needed to recognise the analogy between two different markets (sport and medical grade PPE).	*Challenges:* design, access to materials *Risks / inefficiencies*: fixation on 3D printing approaches when simpler approaches would have been more effective *Approach:* Sharing of knowledge through social media platforms ensured constant learning, adaptation, and access to needed components. Distributed work enables some scale.
Illustrative quotes	*We've launched a company-wide effort, bringing together product designers, engineering, operations and packaging teams, and our suppliers to design, produce, and ship face shields for health workers.*[3]	*Kinnaly said one of his engineers approached him last month with the idea. A design was created, the machinery adjusted and soon after production was underway. The company began by making about 3000 units per week at each location and, as the work force grows more familiar with the process, Kinnaly hopes to ramp up production to 70,000 per week by the end of April.*[4]	*Facebook groups such as Open Source COVID19 Medical Supplies, which has more than 70,000 members, have become dispatch centres, through which hospital workers seek volunteers to print or make supplies, and volunteers trade tips on what materials to use and where to source them, and on sterilisation procedures.* *After bringing in an engineering design firm, the group decided to change tack. Instead of 3D printing, the frames and straps (…) are made from elastic and foam that can be purchased off-the-shelf in bulk form, and cut down either by machine or by hand. Darley says such components can be made in 20 s, compared with several hours through 3D printing.*[5] *While 3D printing offers increasing promise for helping to solve the shortage of medical supplies during the pandemic, it's not so simple to crank up for mass production. "3 M's view is that 3D printing for PPE [personal protective equipment] does not provide the scale we need*[6,7]

[1] www.economist.com/united-states/2020/04/30/americas-makers-and-tinkerers-turn-their-hands-to-ppe
[2] Apple statement: Manufacturing the face shields requires professional level expertise in manufacturing and design, and should only be done by professional engineers or machinists in a factory environment (https://support.apple.com/en-us/HT211142); https://www.washingtontimes.com/news/2020/apr/6/apple-make-and-ship-1-million-face-shields-each-we
[3] https://www.cnbc.com/2020/04/05/apple-will-produce-1-million-face-shields-per-week-for-medical-workers.html
[4] https:// www.nytimes.com/2020/04/07/sports/formula-one-bauer-coronavirus-ppe.html
[5] https://www.nature.com/articles/d41586-020-01246-3
[6] https://www.forbes.com/sites/amyfeldman/2020/03/24/ford-will-work-with-3m-and-ge-to-make-respirators-ventilators-and-n95-masks/#114e816e3dc2
[7] https://media.ford.com/content/fordmedia/feu/ch/de/news/2020/04/30/ford-is-making-face-masks-and-face-shields-to-enable-employees-a.html

perfume production were closely aligned with producing hand sanitiser. The company could thus redeploy its capabilities and achieve large-scale production within days, at scale and without any issues. Repurposing for the luxury brands also enabled them to keep their operations running.

Many distillers and brewers needed additional support to reconfigure and access new supply chains, implement new processes and policies, and change parts of the production (e.g., different packaging). In many jurisdictions, government rules also needed to be relaxed to allow for sanitiser produced by distilleries to be used in hospitals. Finally, some provisions in taxation rules and permits for alcohol production were implemented in some jurisdictions. Overall, though, the knowledge base of both groups was relatively close to the target knowledge base and only some adjustments were needed to succeed.

4.3. Medical face masks: GM, manufacturing sector and the Taiwan's face mask team

For this category, we focused on surgical-grade face masks and N95 masks, both of which require certification and need to meet certain levels of protection.[9] Surgical masks are made of three or four layers of fabric, with a non-woven and electrically charged middle layer that is ultrasonically welded, cut and assembled by specialised machinery. Masks also need to be produced in a sterile environment. While the non-woven fabric determines performance and is usually produced by a specialised manufacturer, the assembly machinery determines the needed scale of production. For N95 masks, fit is also important as it provides necessary level of safety for working in a hospital environment.[10]

While the complexity of the key components was somewhere between medium (protective layer) to low (rest of the components), we assume that the lack of knowledge about the production process posed a significant challenge to non-specialist firms, leading to low outputs, delays and a number of failed attempts.[11] The usual time to set up a N95 manufacturing line is four to six months.[12] Combined with the relative lack of knowledge sharing, the integral architecture of the product and the production process suggest why there were fewer examples of companies attempting to address this demand, relative to the greater number of attempts to produce non-medical masks.[13] Two interesting cases in this category are GM and a handful of other manufacturers and Taiwan's Face Mask Team (TFMT): a consortium of government agencies, industry associations, tool and machinery manufacturers, face mask machinery manufacturers, fabric suppliers, and face mask manufacturers.

There are some stark similarities and differences in the approaches presented in Table 5. Both approaches relied on coordination of supply chains and development of production facilities. The key component, non-woven fabric, could be resourced relatively easily by existing actors in the supply chain[13]. The production line posed higher levels of complexity. Consequently, the scale of production differed significantly. GM relied on its existing facilities and, with some repurposing, created a relatively manual production line that could produce up to 1.5 million mask per month.[14] TFMT took a different approach, with production increasing from fewer than 2 million mask per day at the beginning of the pandemic to 13 million by mid-March and over 20 million by the end of May.[15]

The Taiwanese government recognised that there was a need to (re)

Table 4
Resourcing for Hand Sanitiser.

Product architecture	**Hand sanitizer:** (1) Low product complexity. (2) Modular architecture based on limited number of defined components. (3) Some regulatory specifications for the product. Regulatory specifications for the production process, with specific competencies of staff and certified facilities for handling flammable substances needed. In some jurisdictions, additional product specifications and certifications were needed. Some requirements have been temporarily eased[1]. (4) *Limited fuzziness as components and their proportions are defined and often regulated.*[2]	
Example player (s)	**LVMH, cosmetics producers:***It's in our brand / We are already making it! Kind of…*	**Craft distilleries / breweries:***We are already making it! Kind of…*
Was it successful?	**Safe:***yes, easy to meet the criteria* **Effectiveness:***yes, easy to meet the criteria* **Volume:***yes, by leveraging existing in-house capabilities*	**Safe:***yes, easy to meet the criteria* **Effectiveness:***yes, easy to meet the criteria* **Volume:***partially, not as high volume as commercial production in dedicated facilities*
Objects	Access to certified production facilities and raw materials Knowledge of production processes and certified workforce Supply chain access and coordination capability Spare capacity due to lockdown	Access to certified production facilities (distilling) Access to some raw materials Distilling knowledge
Interpretative frames	(1) Perfect alignment of component with minimal change to architecture knowledge (2) Base domain closely aligned with target domain; no learning required. Minimal modification to production lines (3) *Minimal levels of analogical reasoning were needed as both product characteristics and application are very similar*	(1) Partial alignment of component and architecture knowledge (alcohol vs gel based) (2) Base domain of one component closely aligned with target domain, but required additional learning related to the end product. Some (substantial) modification to production process (3) *Straightforward analogical reasoning (alcohol as disinfectant)*
Deployment strategy	*Challenges*: none *Risks / inefficiencies*: none *Approach:* Existing product capabilities had a direct application with no requirement for new knowledge development. Large-scale production capabilities and need for minimal process and equipment adjustments. Hand sanitiser is often within the same good category (personal care).	*Challenges*: access to packaging, architectural knowledge of the slightly more complex product (gel), and certification. *Risks / inefficiencies*: some production-related hazards. In some jurisdictions switching requires stopping normal production (taxes), which can cause shortages for supply in the future.[5] *Approach:* Existing component capabilities had a direct application but required additional knowledge development/acquisition. Production process needed some amendments. Supply chain access and capabilities were not always sufficient.
Illustrative quotes	*Cosmetics manufacturing is actually a close cousin to pharmacy, and the factory equipment could be quickly repurposed. Sanitising gel requires three main ingredients — purified water, ethanol, hydrogen peroxide and glycerine — all of which LVMH*	*We can't make ventilators, and we can't make masks, but we can make something useful. Making hand sanitizer is deceptively simple but inherently dangerous.* *We're qualified to handle very flammable substances safely. Like all distilleries in New York,*

(continued on next page)

[9] www.fda.gov/medical-devices/personal-protective-equipment-infection-control/n95-respirators-and-surgical-masks-face-masks#s2;https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/883334/Essential_Technical_Specifications_5_.pdf

[10] https://www.washingtonpost.com/lifestyle/2020/07/07/peter-tsai-n95-mask-covid/;https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/;https://www.economist.com/united-states/2020/04/30/americas-makers-and-tinkerers-turn-their-hands-to-ppe;https://smartairfilters.com/en/blog/comparison-mask-standards-rating-effectiveness/

[11] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/

[12] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/;www.taiwantrade.com/news/a-bravery-story-a-taiwan-national-machine-tool-team-for-surgical-mask-production-born-to-fight-against-covid-19-outbreak-1979557.html#

[13] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/

[14] www.gm.com/our-stories/commitment/face-masks-covid-production.html

[15] https://focustaiwan.tw/society/202005250014;https://focustaiwan.tw/society/202009030016

Table 4 (*continued*)

Product architecture	**Hand sanitizer:** (1) Low product complexity. (2) Modular architecture based on limited number of defined components. (3) Some regulatory specifications for the product. Regulatory specifications for the production process, with specific competencies of staff and certified facilities for handling flammable substances needed. In some jurisdictions, additional product specifications and certifications were needed. Some requirements have been temporarily eased[1]. (4) *Limited fuzziness as components and their proportions are defined and often regulated.*[2]	
Example player (s)	**LVMH, cosmetics producers:***It's in our brand / We are already making it! Kind of…*	**Craft distilleries / breweries:***We are already making it! Kind of…*
	already had on hand. In addition to perfumes, the Dior, Givenchy and Guerlain factories also make liquid soaps and moisturising creams for the brands. Those products are similar in viscosity to hand sanitising gel, so LVMH could use its usual filling machines, plastic bottles and pump dispensers. A tall metal tank at the Dior factory usually used to distill scent could be used to mix the ingredients, and a machine for filling up soap bottles drafted into packaging the gel.[3]	*we have spark-resistant lighting, explosion-proof pumps, our electric is set at least five feet off the floor, and our staff is certified in fire protocols and spill response. Distillers needed to know how to make it safely, correctly and to make it effective – that's a lot of knowledge to transfer very quickly.*[4] *The transition from alcohol production to hand sanitizer is fairly easy - we have the equipment and just needed a few supplies.*[5]

[1] https://www.gov.uk/guidance/producing-hand-sanitiser-and-gel-for-coronavirus-covid-19;https://www.ttb.gov/images/newsletters/archives/2020/ttb-newsletter03172020sp.html;

[2] https://www.who.int/gpsc/5may/Guide_to_Local_Production.pdf;https://www.fdabasics.com/fda-requirements-for-hand-sanitizers/

[3] https://www.ft.com/content/e9c2bae4-6909-11ea-800d-da70cff6e4d3

[4] https://news.cornell.edu/stories/2020/04/cornell-aids-distillers-making-hand-sanitizer

[5] https://www.forbes.com/sites/fredminnick/2020/03/18/white-house-works-with-distillers-to-increase-hand-sanitizer-production/#4850eeb27fcd

build lost capability at the national level by increasing the number of production lines. As the remaining few mask machine manufacturers initially had no capacity or willingness[16] to address the need, the government called for industry to help. Taiwan Machine Tool & Accessory Builders Association (TMBA) mobilised around 30 machine and tool makers from across the supply chain, which were joined by three main government industrial research institutes.[17] Nonetheless, the companies realised that none of them had prior experience in developing a mask making machine and that there are significant differences between the capabilities required to handle the (soft) material and their existing competencies. At first, this consortium considered reverse engineering existing machines, but it concluded that achieving the required efficiency and precision without access to tacit knowledge that the machine manufacturer possessed would be impossible. Additionally, the government introduced a range of levers (e.g., a dynamic payment bonus system) to motivate local manufacturers.[18] It also specified that all future public purchases of masks would give preference to locally-made masks.

The example illustrates high levels of reflexivity to recognise and address *expertise gaps* between base and target domains, rather than focusing on the similarities between them. As we illustrate in the next section, the lack of such reflexivity can be expensive.

4.4. Ventilators

Ventilators are highly specialised, complex equipment that need to adhere to stringent manufacturing, testing and regulatory standards. They include highly specialised parts that might be difficult to replace, advanced sensors, and algorithms. Misadjusted flow, pressure, or pace can lead to irreversible lung damage. Consequently, they require well-trained specialists and must be able to operate in a busy hospital environment.[19]

Because of the close coupling between a patients' condition and the equipment's complexity, ventilators rely on integral architecture. Design fuzziness is limited. Simpler designs, such as AmbuBag, are often limited to emergency use or as a temporary solution until a fully functional ventilator is available.

Despite the complex nature of ventilators, a vast mobilisation of enthusiasts, university teams, and a range of organisations joined the efforts to produce them. These organisations included FitBit, GM, Ford, F1 teams, Airbus, and NASA. Some tried to "do it alone," and others partnered up or formed consortia. Some decided to work with existing, and often approved, designs and producers, while others attempted to design a ventilator from scratch. In the United States, some companies were compelled to speed up their efforts by President Trump, who invoked the Defense Production Act.[20] We focus our analysis on four distinct approaches, as illustrated in Table 6.

From Table 6, several observations can be made. First, the "Eager Helpers" approached the task from their interpretative frame; they saw a ventilator as a simple air-moving machine or a simple mechanical device. Companies in this group focused on their existing frames and the similarities to the product they were trying to resource. This led them to underestimate the complexity and the highly integral architecture and led them to attempt to develop a simpler ventilator. This approach led to designs that often could be deployed only for emergency use. It was also difficult to obtain approvals for new, unproven designs. Medical equipment manufacturers argued that "it's easy to say you can just design a ventilator but the safety isn't just in the design".[21]

NASA, which also opted to develop a new design, approached the task differently. First, it relied on its prior experience of developing some medical devices and collaboration with the medical community. Second, it used reflexive analogical reasoning to focus on the expertise it lacked before it started on the project. It thus relied on established relationships with the medical engineering community and the FDA. Third, it had developed portable devices for medical use.[22] Its VITAL design is tailored specifically for emergency use and has a limited life span, thus

[16] The chief reason is related to their prior experience of bearing the cost of scaling up production during SARS outbreak, only to be left with overcapacity and idle machines. Once the epidemic was over, due to the Government's 'lowest price purchase guideline' policy most mask purchased by hospital would be from China. Put differently, for firms investing in short-term capacity building seemed like a costly mistake to be repeated. This challenge was addressed by government reassurance to commit to 'Made in Taiwan' masks for government-run laboratories and hospitals after the pandemic.

[17] Industrial Technology Research Institute (ITRI), Metal Industries Research Development Centre (MIRDC), Precision Machinery Research & Development Centre (PMC).

[18] www.twreporter.org/a/covid-19-mask-national-team-taiwan-can-help

[19] www.newyorker.com/magazine/2020/05/18/the-engineers-taking-on-the-ventilator-shortage;www.wired.com/story/race-build-more-ventilators-coronavirus/;www.economist.com/international/2020/03/26/scientists-and-industry-are-dashing-to-make-more-ventilators

[20] https://www.theguardian.com/us-news/2020/mar/27/trump-defense-production-act-coronavirus-gm

[21] www.theguardian.com/business/2020/may/04/the-inside-story-of-the-uks-nhs-coronavirus-ventilator-challenge; see also www.economist.com/international/2020/03/26/scientists-and-industry-are-dashing-to-make-more-ventilators;https://fortune.com/2020/03/25/coronavirus-ventilator-production-problems-shortage-national-strategic-stockpile/

[22] https://edition.cnn.com/2020/05/01/health/nasa-ventilator-fda-approval-wellness-scn/index.html

addressing the need only partially.

The third distinct approach relied on a consortium of companies, often including a ventilator manufacturer or access to an approved design and licence. These consortia focused on leveraging the range of capabilities across the partnership. For example, Siare's partnership with Ferrari and Fiat Chrysler had the latter two focus on supplying one part. In other cases, established manufacturers such as GM were tasked with developing large-scale production systems, but relied heavily on the know-how of the experienced ventilator manufacturers. Some of these companies acknowledged the importance of tacit production knowledge and relied on augmented reality or sent their engineering teams to observe, film, and photograph the production processes.[23] As one manufacturer pointed out, it is far more efficient to expand production when the know-how and approval are already available.[24] Those partnerships relied on complementary expertise and deployed their objects where they could add the most value. In those partnerships, automakers played a contractor role to medical device manufacturers, which held the required licence (certificate) and were thus responsible for safety. Many consortia focused on understanding their complementary capabilities and on mapping and accessing missing competencies. As explained by a Ford executive, "our value-add was to apply high-volume manufacturing expertise that you see uniquely in the auto industry. We found quite a few places where you could change a process to improve cycle time, and move it around, so that the throughput of the whole assembly process got more things out of the back end".[25]

The fourth approach also relied on a consortium of companies, but with governments coordinating effort and the lack of an established local medical equipment manufacturer. Based on the successful mobilisation of face mask manufacturing and prior experience of technology acquisition and dissemination (Hung, 2002), the Industrial Technology Research Institute (ITRI) in Taiwan coordinated efforts with the industrial community to redevelop and build ventilators based on an approved prototype that was released earlier under a special "permissive licence" by a prominent ventilator manufacturer (Medtronic). This approach relied on the realisation that the community possessed strong component-level expertise, but lacked architectural understanding of the product. The partnership relied on ITRI's R&D capabilities and its medical field research (e.g., biotechnology) to provide testing capabilities. It can be assumed that ITRI will pass the licence and know-how to a private company (c.f. Hung, 2002), with the goal of seeding a new industry.[26]

5. Discussion and implications

When the pandemic began, many companies attempted to repurpose their resources and capabilities to provide needed products. These efforts suggest that resources can be used in various ways, reflecting how individuals enact them through interpretative frames (Feldman & Worline, 2011; Penrose, 1959; Sonenshein, 2014). The resourcefulness literature has proposed multiple strategies for using resources. These include bricolage as a way to make do with what you got (Baker & Nelson, 2005), creative use of resourcing through sensemaking (Ganz, 2000; Sarasvathy, 2001), envisioning different applications of objects (Sonenshein, 2014), and deploying and recombining resources through collaboration and open innovation (Deken et al., 2018). Furthermore, experimentation with different frames and practices can lead to new ways of conceptualising how objects can be used (Feldman & Worline, 2011; Kannan-Narasimhan & Lawrence, 2018). Yet we have little understanding of the boundary conditions for resourcefulness and the conditions under which different resourcing strategies can be effective. We contribute to this discussion by proposing that the success of different resourcing initiatives reflected the interrelations among the objects owned or accessed by firms, the interpretative frames used to deploy those objects in new contexts, and the architecture and institutional rules of the product resourced. As our findings indicate, the different resourcing approaches summarized in Table 2 can lead to different outcomes depending on the interrelations among the dimensions in our framework.

Appreciating these distinctions can help managers understand the usefulness of each approach for different product categories. Indeed, failure often occurs when managers underestimate the complexities of product architecture and the differences between the base and target knowledge domains. When the target product is less complex and/or has a modular architecture, as face shields and hand sanitiser do, it is easier for firms that operate in relatively similar source domains or that possess relevant capabilities to redeploy their capabilities in the new context (Mastrogiorgio & Gilsing, 2016). Low product complexity means design specifications are fuzzy and thus allows a firm to experiment more and extend analogical interpretative frames across contexts (Sonenshein, 2014). As product complexity increases and the relations between subcomponents become more integral, however, product specifications become more defined and there is less room for experimentation (Sanchez, 2008; Ulrich, 1995). In such cases, the need for coordination increases because the firm attempting to enter the new domain may lack knowledge about certain components. These firms can contribute their manufacturing capacity or supply chain capabilities to help specialist firms ramp up their production. Our examples also suggest that production can be more challenging than the product design itself. Even when the product complexity is medium, as it is for medical face masks, success in achieving scale is affected by access to both the tacit dimension of assembly of production machinery and to industrial engineering capabilities.

In our study, the most challenging context for resource redeployment involves highly complex products with integral architecture such as ventilators. The design and manufacturing of these products require tacit knowledge of the integral relations among components (Ulrich, 1995) and of strict regulatory specifications. The scope for resource transfer across contexts is thus limited. In these environments, non-specialist firms might fail to recognise the deep structural differences between their home and target domain while overemphasizing surface similarities in some components (Gary et al., 2012). We saw several examples of firms that analogically extended their frames without considering the differences between contexts. Their efforts resulted in ventilators unsuitable for ICU use or designs that failed to gain regulatory approval.[27] Thus, successful resourcing in this context entails a coordinated approach through a consortium where specialist firms take the lead and non-specialist firms focus on helping to scale up production. Firms using this approach seemed to realise the applicability of their knowledge and frames in the new context was limited and adapted their interpretative frames by being reflexive (Hibbert et al., 2016). They may have focused less on potential similarities between the home and target knowledge domains than they did on the differences. In the case of the medical masks, cooperation with specialised producers of machinery and masks, and a consequent access to tacit knowledge, determined the success of scaling up the production of medical face masks: while

[23] www.themanufacturer.com/articles/augmented-reality-is-playing-a-vital-role-in-supporting-ventilatorchallengeuk;https://www.wsj.com/articles/gm-hustles-to-pump-out-ventilators-to-fight-coronavirus-amid-trump-barbs-11585586925

[24] https://fortune.com/2020/03/25/coronavirus-ventilator-production-problems-shortage-national-strategic-stockpile/

[25] https://chiefexecutive.net/better-ideas-fords-approach-got-pandemic-response-flowing/

[26] https://technews.tw/2020/05/26/tw-masks-8-million-0601/

[27] https://www.independent.co.uk/sport/motor-racing/formula1/coronavirus-f1-teams-ventilator-uk-order-cancelled-red-bull-renault-a9463711.html; https://uk.reuters.com/article/us-health-coronavirus-britain-ventilator-idUKKCN21U0UI

coordination efforts helped TFMT, lack of such coordinated approach is being attributed to the chronic shortages of N95 in the US context.[28] Noteworthy, the difficulties are related to the architecture of the production process rather than to the the specialised fabric (a key component) as this could be relatively easily resourced for[27].

Finally, our analysis highlights the role policy makers play in supporting resourcing strategies: our data suggest that such interventions can coordinate knowledge and interests across actors (Hung, 2002), thus mitigating market and IP risk and "stretching" design fuzziness by amending regulations. Such coordination can enhance the capabilities of existing firms through coopetition, which is cooperation between competing organisations in which resources and capabilities are shared with competitors to achieve shared goals (Crick & Crick, 2020) and potentially seed new industries. As explained by Taiwan's Deputy Minister of Economic Affairs, it was better to "use communication instead of prohibition, and "negotiate" with manufacturers to get good results". More recently, Taiwan's government allowed firms to export production machinery, opening new growth opportunities.[29] Surprisingly, most governments did little to coordinate the efforts among organisations and sometimes seemed to lead companies into dead ends. For example, after providing misleading specifications, the UK government cancelled numerous orders.[30] Similarly, an overestimate of demand in the United States led to contract terminations and uncertainty.[31] There is also evidence that uncertainty about future demand will discourage companies from investing in more costly resourcing strategies.[32] Using our Fig. 2, in which we plotted the different product categories on two dimensions, we can superimpose these dynamics, as illustrated in Fig. 4.

Successful resourcing efforts thus depend on understanding product architecture and complexity. As this understanding increases, firms must become more reflexive to enable analogical thinking (Hibbert et al., 2016). At the same time, the need for coordination and support increases, particularly from government institutions. Such support can include amending the legal framing and the institutional context, aiding collaborative knowledge sharing and development, which might require provisions for protecting IP, and addressing the potential impact on existing markets that can affect current producers.

5.1. Theoretical and practical implications

Our study contributes to a better understanding of which resourcing strategies are effective under different conditions. We begin to fill this gap by integrating insights from the resourcefulness literature with those from the product architecture literature. Our study indicates that when firms consider whether to redeploy their resources in new contexts, their managers need to be both reflexive and strategic. Accurate assessment of a product's architecture and firm's capabilities can save significant amount of money. Indeed, the case of ventilators illustrate how easy it is to focus on the component level and ignore a product's architectural complexity. As this complexity increases, a firm needs to consider working with partners that possess complementary skills. Managers' ability to reason analogically can be improved through tools and questions that induce reflection on the structural relations between different domains (Gary et al., 2012; Gentner, Loewenstein, & Thompson, 2003). As such, our framework and proposed typology provide a simple reflective tool that practitioners can use to decide the appropriate resourcing strategy.

Our study also highlights the benefits that organisations can accrue by undertaking these resourcing initiatives. Although the efforts are ongoing and not all the initiatives or their impact can be ascertained, existing reports and our analysis allow us to outline the short and (potential) long-term effects of resourcing initiatives on relevant organisations, sectors, and economies. In the immediate and short term, in addition to helping in resourcing the critically needed medical products, the main benefits include remaining operationally active, thus avoiding job loses or (costly) production line closures. Furthermore, press coverage of the initiatives provided brand exposure, which can improve the firm's image, reinforce its brand strategies, or signal particular industrial capabilities to potential partners.[33] Finally, organisations that undertook a collaborative approach managed to expand their networks, which can lead to enhancing their collaborative capability (Crick & Crick, 2020; Hibbert & Huxham, 2005).

In the long term, resourcing initiatives can enhance organisations' innovation capability when firms work with new partners from different fields, thus broaden their interpretative frames[34] (Chesbrough, 2020). Second, as a result of learning from these initiatives, firms may consider diversifying into new markets or product categories.[35] While not all companies may be interested in entering those new markets,[36] some already have begun to develop related products as part of their regular offering (e.g., face shields as fashion items[37]). Others have started to develop new segments of products (e.g. commemorative face masks for special occasions), entered into new distribution relationships or collaborative arrangements (e.g. a leading Taiwanese airline in collaboration with one of the members of the TFMT developed a new "Passenger Personal Protection Kit" containing specially designed mask and disinfectant for long haul flights).[38] As the developments we report are ongoing, we can only assume other implications will become visible and offer interesting areas for future research.

Finally, we found that governments facilitated effective resourcing. First, policy makers can adjust regulatory frameworks to increase fuzziness in product design. This effort can allow a broader range of actors to redeploy their resources. Second, policy makers can amend public procurement policies to ensure future demand as a lever to align the interests of the industry / key stakeholders, and thus be more willing to invest.[39] Third, policy makers can assure firms that are wary of sharing their know-how by providing reassurances and addressing potential IP

[28] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/;www.twreporter.org/a/covid-19-mask-national-team-taiwan-can-help

[29] https://www.ettoday.net/news/20200817/1786856.htm;https://www.knh.com.tw/homepage.html

[30] https://www.independent.co.uk/sport/motor-racing/formula1/coronavirus-f1-teams-ventilator-uk-order-cancelled-red-bull-renault-a9463711.html;https://www.theguardian.com/business/2020/may/04/the-inside-story-of-the-uks-nhs-coronavirus-ventilator-challenge

[31] https://www.nytimes.com/2020/03/26/us/politics/coronavirus-ventilators-trump.html;https://www.ksn.com/news/health/coronavirus/coronavirus-in-kansas/future-uncertain-for-spirit-aerosystems-employees-after-ventilator-orders-canceled/

[32] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/

[33] https://www.voanews.com/covid-19-pandemic/unlikely-story-first-made-vietnam-ventilators-fight-covid-19;https://www.ettoday.net/news/20200817/1786856.htm

[34] https://www.huffpost.com/entry/medtronics-leadership-amidst-pandemic-proves-the-power-of-innovation-and-inclusion_n_5e99d19dc5b6ea335d5ac367;https://chiefexecutive.net/better-ideas-fords-approach-got-pandemic-response-flowing/

[35] https://www.ettoday.net/news/20200817/1786856.htm

[36] https://medicalxpress.com/news/2020-09-gm-ford-finish-ventilators.html

[37] https://www.fastcompany.com/90550249/louis-vuittons-new-face-shield-doesnt-just-protect-you-from-covid-19

[38] https://www.taiwannews.com.tw/ch/news/4001966;https://www.csd.com.tw/news

[39] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/;www.twreporter.org/a/covid-19-mask-national-team-taiwan-can-help;https://www.youtube.com/watch?v=ZvS3S8058Hk&feature=youtu.be

Table 5
Resourcing for Medical Face Masks.

Product architecture	**Medical Face Masks:** (1) Low to medium product complexity, with medium-high complexity of production process[1]. (2) Integral architecture based on limited number of components and highly dependent on production processes, based on tacit or protected by trade secrets knowledge. (3) Regulatory specifications for the product in terms of filtration and sterilisation, with more demanding specifications for the use in ICU context. Higher requirements for N95. (4) *Relatively high fuzziness in terms of design / architecture and components. Low fuzziness in production process at large scale / efficiency*[2]	
Example player (s)	**GM, manufacturing sector:***Eager helpers*	**Taiwan's Face Mask Team:***We are in it TOGETHER / Not so eager helpers*
Was it successful?	**Safe:***yes, although need to meet medical (as opposed to industrial) safety criteria* **Effectiveness:***yes, as long as at the lower end (medical but not N95) face masks* **Volume:***no. High volume could not be achieved due to part-manual process*	**Safe:***yes, capability already within the consortium* **Effectiveness:***yes, capability already within the consortium* **Volume:***yes, capability already within the consortium for large scale production*
Objects	Production facilities / equipment Access to supply chain Knowledge of manufacturing processes	Expertise in equipment production Expertise in mask production Coordination of knowledge and production at a national scale Coordination of supply chain for technically complex equipment
Interpretative frames	(1) Relatively specialised components (non-woven microfibre fabric) and simple architecture (3 layers of material welded together; sealed design for N95). Large scale manufacturing requires specialist machinery (ultrasonic welding, sterilisation) (2) Distant base domain from target domain in both component and manufacturing process (3) *Medium levels of analogical reasoning to identify suitable materials (from noise dumping to protective mask); straightforward analogical reasoning to identify the manufacturing capability fit*	(1) Perfect alignment of component knowledge but significant (initially) lack of architectural knowledge (2) Base domain was relatively close to the target domain (i.e. production of machinery), there was specialised tacit knowledge required for efficient production at large scale (3) *Analogical reasoning demanded levels of reflexivity to focus on the needed expertise and addressing this gap through engaging with experts outside of the company*
Deployment strategy	*Challenges*: understanding / meeting the regulatory requirements for higher grade masks; achieving scale requires specialised production lines. *Risks / inefficiencies*: mostly lowscale production; technical challenges, including quality requirements[3], often limited to lower grade / unsuitable for hospital use. *Approach:* Mobilisation of suppliers to develop and deliver new, suitable material. Use of existing modified manufacturing processes and equipment for assembly. Relatively low scale production only as the existing production equipment is unsuitable for assembly at scale.	*Challenges*: achieving high levels of efficiency (tacit knowledge dependence); IP issues; resolving uncertainty of future demand, coordination of multiple interests. *Risks / inefficiencies*: IP misappropriation; lack of involvement of key players (competence); overproduction and too much stock at the end of the crisis that can demotivate mask producers form investing in a scale up. *Approach:* Government-level coordination of knowledge sharing and additional levers for motivating engagement. Government purchase of the machinery and resolving potential IP issues. Active alignment of stakeholder interests (e.g. dynamically adjusting bonus systems to encourage mask makers to work overtime and weekends[8]) and securing future demand (change of public procurement policies). Long-term strategy to build national capabilities beyond the current crisis.
Illustrative quotes	*GM worked with automotive suppliers to develop the three layers of fabric in the masks. These companies typically provide GM with sound-deadening insulation found in doors, headliners and trunks, but they quickly altered their production processes.*[4] *Window-shade manufacturer uses the same nonwoven polyester material used in medical gear, and engineers there started prototyping surgical masks and gowns (…) The company (…) has been producing lower-grade surgical masks. (…) We're becoming quickly educated in an industry which was a bit foreign to us*[5] *An inspection revealed that the FFP2 masks did not protect the face properly or had defective filter membranes.*[3] *But when GM started making N95s, engineers with expertise in car interiors and air bags were charged with figuring out the process from scratch, the company said. Although they received advice from major mask makers, there were no groundbreaking corporate partnerships this time. The first N95s GM made were rejected by NIOSH. The second design didn't correctly fit most people. Other potential manufacturers went through the same challenges as GM, failing tests and making flat-fold N95s that experts worry do not offer a tight enough seal. "If there was some kind of intellectual sharing, they wouldn't be doing that,".*[9]	*Rapidly increasing mask production will not be easy, as Taiwan's local mask industry is not very profitable and most manufacturers relocated elsewhere in the world more than 20 years ago. (…) Taiwan's remaining mask production equipment manufacturers are very small in size with limited staff and it will take four to six months to build 60 lines. Overall, it is extremely a challenge for mask production equipment manufacturers to fulfill the government goal.* *The machine tool manufacturers input its 30–40 years of production experience to help the mask production equipment manufacturers to shorten their production time. First, they dismantle the machine, classify the machine parts, and set the standard SOP of the mask equipment production line assemble work flow. They then developed modular production lines and assigned different machine tool companies to assist in a different operating cell. Everyone can therefore focus on their part and optimize their assemble efficiency.*[6] *[machine manufacturers] understood that reverse engineering may not be able to achieve that critical 5% of secret [as] the specialty of machine tools is metal cutting, but the masks are different - the cloth is soft. The adjustment of the two when feeding is completely different expertise. Their machine can only achieve 95%, without the key 5% technology of the mask machine factory. The production efficiency of the machine may be the difference between 30,000 tablets per day and 100,000 tablets per day.*[7]*

[1] https://www.thomasnet.com/articles/other/how-surgical-masks-are-made/#_Types_of_Masks;https://www.fda.gov/medical-devices/personal-protective-equipment-infection-control/n95-respirators-and-surgical-masks-face-masks#s2;https://www.youtube.com/watch?v=PG5bI8Z7ifc&feature=youtu.be;https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/

[2] https://www.youtube.com/watch?v=ZvS3S8058Hk;https://www.youtube.com/watch?v=PG5bI8Z7ifc;https://www.gm.com/our-stories/commitment/face-masks-covid-production.html

[3] https://www.dw.com/en/coronavirus-netherlands-recalls-defective-masks-bought-from-china/a-52949216

[4] https://www.gm.com/our-stories/commitment/face-masks-covid-production.html

[5] www.wsj.com/articles/new-york-manufacturers-mobilize-to-make-face-masks-medical-gowns-11585224003

[6] https://www.taiwantrade.com/news/a-bravery-story-a-taiwan-national-machine-tool-team-for-surgical-mask-production-born-to-fight-against-covid-19-outbreak-1979557.html#

[7] https://www.youtube.com/watch?v=PG5bI8Z7ifc*NOTE: translation from Youtube interview. Not a direct quote.

[8] https://www.twreporter.org/a/covid-19-mask-national-team-taiwan-can-help

[9] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/

Table 6
Resourcing for Ventilators.

Product architecture	**Ventilators:** (1) High product complexity[1] (2) Integral architecture (high number of specialised components, software, testing, …) (3) Overall demanding regulatory specifications for the product (some variation based on geography or type of ventilator) and the production process, with licence attached to a specific manufacturer who bears responsibility for safety of the equipment[2] (4) *Very limited fuzziness in terms of architecture, some limited fuzziness in terms of components.*[3]			
Example player(s)	**Dyson, Tesla:***Eager helpers / it's in our brand*	**NASA:***we are already making it! Kind of… / it's in our brand*	**VentilatorChallengeUK; Vermontilator; GM*&GE Healthcare; Ford:***we are in it TOGETHER / Not so eager helpers*	**Taiwan Ventilator Team**: *we are in it TOGETHER*
Was it successful?	**Safe:***no, failed to get an approval* **Effectiveness:***no, most could be used in very limited capacity* **Volume:***not clear as most did not enter production*	**Safe:***yes, approved* **Effectiveness:***limited due to limited lifespan and only emergency use* **Volume:***not clear, probably reasonable volume that could match regular production, but not as high volume as others could achieve*	**Safe:***yes, most got approved* **Effectiveness:** ***mixed form****limited to relatively high, most could be used in limited capacity* **Volume:***yes, most could achieve reasonably high volume, often higher than regular production*	**Safe:***yes, approved* **Effectiveness:***yes, improving proven design* **Volume:***not clear as most did not enter production. Based on the assessment of existing manufacturing capabilities and supply chain in place, can likely yes*
Objects	Design and production capabilities in the mechanical engineering domains (broadly) Access to production lines and skilled staff Supply chain management capabilities Financial resources	Design and production capabilities for highly complex equipment Established relationship with medical equipment community and with local regulatory agency (access to expert knowledge on medical devices) Prior experience in medical device development (mix of tacit knowledge and collaborative capability)	Manufacturing and industrial engineering capabilities Access to and power to orchestrate specialised supply chain Medical device manufacturing and market expertise Specific component capabilities Existing ventilator design Approved design or experience in obtaining approval Integrated circuit design and manufacturing capabilities *These capabilities were distributed among members*	Knowledge transfer and collaborative product development [a] Rapid prototyping [a] Medical research and testing [a] Medical equipment components manufacture [b] Manufacturing capabilities [b] Software development capabilities [b] Integrated circuit design and manufacturing capabilities [b] *[a, b]indicates how these capabilities were distributed among:[a]ITRI;[b]industry members*
Interpretative frames	(1) (Potential) familiarity with the component but lacking understanding of the architecture (2) Base domain significantly different from target domain, except for engineering principles (3) *Analogical reasoning was clouded by focus on the mechanical design and the airflow aspect of a ventilator, at the expense of regulatory, safety, and continuous monitoring issues*	(1) Some familiarity with the component and architecture of the product and the process (2) Home and target base relatively distant, although overlaps exist. The gap is bridged by existing network relationships (3) *Analogical reasoning demanded reflexivity to focus on the lack of expertise and engaging with experts outside of the company*	(1) Medical device partner possessing both the component and architectural knowledge, while partners often limited to some component knowledge only (2) The large gap between the domains is bridged through the network and knowledge sharing practices (e.g., augmented reality) (3) *Analogical reasoning demanded high levels of reflexivity to focus on mapping of the complementarities and reaching to partners with needed expertise*	(1) Knowledge of the component but no knowledge of the architecture (2) Base domains distant from the target domain (e.g., no expertise in ventilator or similar medical device manufacturing), some overlap in medical components and R&D capabilities (e.g., prototyping, testing) (3) *Analogical reasoning to bridge the missing expertise in ventilator development and certification from prior R&D experience of ITRI*
Deployment strategy	*Challenges*: lack of medical devices manufacturing expertise; obtaining relevant certifications; understanding of the medical environment. *Risks / inefficiencies*: misinterpreting of the product as a "simple air moving machine" and disregarding the (stringent) regulations. Machines could often be used for only a short time as a bridge / emergency solution; no market after the pandemic[34] *Approach:* Lacked realistic assessment of technology. Often opting for complete re-design of existing products. Most work was undertaken in-house and relied on existing capabilities, forcing to focus on the less complex types of ventilators (AmbuBag) which could gain necessary approvals for emergency use.	*Challenges*: leveraging the existing network to meet the demands of the unknown market; engaging partners to build a potentially competitive product to their market. *Risks / inefficiencies:* the machine produced has limited lifespan. *Approach:* Leveraging the existing network. Reflexive assessment. Engaging and relying on medical device community and relationship with FDA. Design required relaxing of some of the rules. Potential risk of saturating the market mitigated by limited lifespan.	*Challenges:* coordinating the network to achieve required quality and safety; sharing of knowledge, potential IP issues; access to necessary parts that are unavailable. *Risks / inefficiencies:* in some cases, only lesser functionality machines could be delivered; obtaining necessary approvals; safety issues; saturating the future market or creating own competitors; sharing of obsolete blueprints. *Approach:* Reflexive assessment and reaching out for missing expertise. In most cases the teams started with focusing on the task complexity (e.g. understanding of how lungs and ventilator work together) and needed expertise. Resourcing strategy based on complementarity capabilities. Partnerships spanned from cooperative to collaborative approaches.	*Challenges:* lack of medical devices manufacture expertise; access to IP / device designs. *Risks / inefficiencies:* settling on subpar/ obsolete design; obtaining international certifications; no local established producers to 'take over'. *Approach:* R&D cost is covered by the government, with technology transferred to industry once mature; obtaining an IP with a plan to upgrade it in-house.[11] Leveraging lack of local competition to mobilise the industry and seed a new industry (technological upgrading). Long-term strategy to build national capabilities beyond the current crisis.
Illustrative quotes	*Firms with no prior experience were increasingly bullish that they could design and build a prototype within weeks.* *Without the independent regulatory teams, most of these projects would have gone nowhere. (…). It's easy to say you can just design a ventilator but the safety isn't just in the design, it's about how you make them, the quality management, servicing*	*We specialize in spacecraft, not medical device manufacturing. But excellent engineering, rigorous testing and rapid prototyping are some of our specialties.* *Building a medical device is new. It goes against our culture to do something quickly in a domain where we're not experts.*[8] *At first, the engineers began in the spirit of Apollo 13. (…) can we at*	*The only group to have secured regulatory approval and supplied ventilators to the NHS in significant numbers is VentilatorChallengeUK, a consortium of manufacturers that focused on scaling up production of proven devices, rather than building new ones.*[10] *A lung analogue was brought in from the hospital for testing; a regulatory expert began preparing an emergency report for the Food and Drug Administration, which had created a*	*U.S. ventilator giant Medtronic shared the basic design specifications of its PB 560 portable ventilator, following which ITRI coordinated resources needed to produce a ventilator, including mechanisms, electronic controls, firmware, software, and data system integration, and it successfully sourced more than 500 key components, which demonstrates the outstanding flexibility and strengths of Taiwan's supply chain.*

(*continued on next page*)

Table 6 (*continued*)

Product architecture	**Ventilators:** (1) High product complexity[1] (2) Integral architecture (high number of specialised components, software, testing, …) (3) Overall demanding regulatory specifications for the product (some variation based on geography or type of ventilator) and the production process, with licence attached to a specific manufacturer who bears responsibility for safety of the equipment[2] (4) *Very limited fuzziness in terms of architecture, some limited fuzziness in terms of components.*[3]			
Example player(s)	**Dyson, Tesla:***Eager helpers / it's in our brand*	**NASA:***we are already making it! Kind of… / it's in our brand*	**VentilatorChallengeUK; Vermontilator; GM*&GE Healthcare; Ford:***we are in it TOGETHER / Not so eager helpers*	**Taiwan Ventilator Team**: *we are in it TOGETHER*
	them. It's not an innovation programme, it was there to meet a clinical need.[5] *Musk responded saying the tech components produced at his Tesla and SpaceX factories were "sophisticated" and ventilators were "not difficult" in comparison. Tesla makes cars with sophisticated HVAC systems (…) Ventilators are not difficult, but cannot be produced instantly.*[6] *I think the idea of automotive manufacturers or indeed any manufacturer that is not well-versed in the production of medical devices somehow quickly retooling and making an alternative product is very naïve.*[7]	*J.P.L. design a ventilator that uses parts scrounged from a garage, or from a vacuum cleaner, or a Home Depot? That idea lasted about six hours. They next considered developing a reference design and open-sourcing it for do-it-yourselfers. A doctor who had come in to consult waved them off, explaining that his hospital would only use a device that had been F. D.A.-approved. "He dropped a lot of reality on everybody about the level of engineering we'd have to do".*[9]	*special approval process for stopgap ventilators; and several local contract manufacturers were lined up so that the device could be mass-produced. For G.M., Ventec has created a simplified version known as the V + Pro. G.M. flew six engineers to study the production process. "We took a lot of pictures and a lot of video,". The VOCSN has around seven hundred parts; the V + Pro, around four hundred. By e-mailing lists of parts to around seventy of its "Tier 1" suppliers, G.M. was able to secure all of them by the following weekend. Suppliers had to adapt production lines to new specifications; they had to ask their own suppliers to do the same.*[9] *It was tough for Ford and other big industrial companies to pivot into making medical equipment. Quite apart from the (obvious) challenge of sterilising previously filthy assembly lines, it was almost impossible to find basic manufacturing materials when cross-border supply chains collapsed during lockdown*[13]	*ITRI has seized upon three factors to this end. The first key is software: The team successfully interpreted the software program and functions of the Medtronic prototype. The second key is system components: The team actively sought out components from the up-, mid-, and downstream industrial chain, including microprocessors, sensors, fan motors, blowers, and masks, and even is producing some items on its own* via *3D printing. The third key is system validation: To domestically produce the key components of the ventilator is the first step. Then the prototype will need to pass software and hardware testing, calibration and validation.*[12]

[1] www.fortune.com/2020/03/25/coronavirus-ventilator-production-problems-shortage-national-strategic-stockpile/;www.wired.com/story/race-build-more-ventilators-coronavirus/;www.newyorker.com/magazine/2020/05/18/the-engineers-taking-on-the-ventilator-shortage

[2] www.wired.com/story/race-build-more-ventilators-coronavirus/;www.theguardian.com/business/2020/may/04/the-inside-story-of-the-uks-nhs-coronavirus-ventilator-challenge

[3] www.economist.com/international/2020/03/26/scientists-and-industry-are-dashing-to-make-more-ventilators;

[4] www.theguardian.com/business/2020/apr/27/uk-to-halt-several-ventilator-projects-after-fall-in-demand

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[7] www.wired.com/story/race-build-more-ventilators-coronavirus/

[8] https://edition.cnn.com/2020/05/01/health/nasa-ventilator-fda-approval-wellness-scn/index.html

[9] https://www.newyorker.com/magazine/2020/05/18/the-engineers-taking-on-the-ventilator-shortage

[10] www.theguardian.com/world/2020/apr/24/dyson-will-not-supply-ventilators-to-nhs-to-treat-covid-19

[11] this strategy has been used in other industries and technologies by ITRI in the past. See, for example, Hung (2002)

[12] markets.businessinsider.com/news/stocks/itri-unveils-taiwan-s-first-medical-grade-ventilator-prototype-1029181138?op=1

[13] www.ft.com/content/049a36b7-a9f9-41b6-8571-134a6c2563d4

issues. They can also provide access to needed technology through enticing ground-breaking corporate partnerships and knowledge sharing.[40] Moreover, policy makers can coordinate complex networks of partners to enable complementary resourcing. The examples of the ventilator challenge and the scaling up of mask production illustrate how policy makers can influence these outcomes. Finally, our analysis demonstrates the nested and multi-layered nature of business environments and the intrinsic interrelatedness that drive development of markets and business ecosystems (Möller et al., 2020).

6. Limitations

As with any research, this study has limitations. First, we rely solely on secondary data, which can be incomplete and subject to our (mis) interpretation. However, considering the context, this reliance can be a strength. Second, the story of the pandemic is still unfolding. For example, we defined success as an initiative that delivers safe and effective products at volume. Yet an initiative that failed by this criterion might eventually help an organisation succeed. Learning from failure can lead to organisational transformation and changes in managerial interpretative frames (Madsen & Desai, 2010). Finally, our own frames of reference affect our interpretations of the cases. Again, we see pluralism and alternative explanations as a strength rather than a limitation (Elsahn et al., 2020). Going forward, our results open paths for further research focused on the different mechanisms to coordinate resourcing activities, the role of the government institutions and regulations, issues related to IP or, indeed, market dynamics.

[40] https://www.washingtonpost.com/graphics/2020/local/news/n-95-shortage-covid/

Conflict of interest

None.

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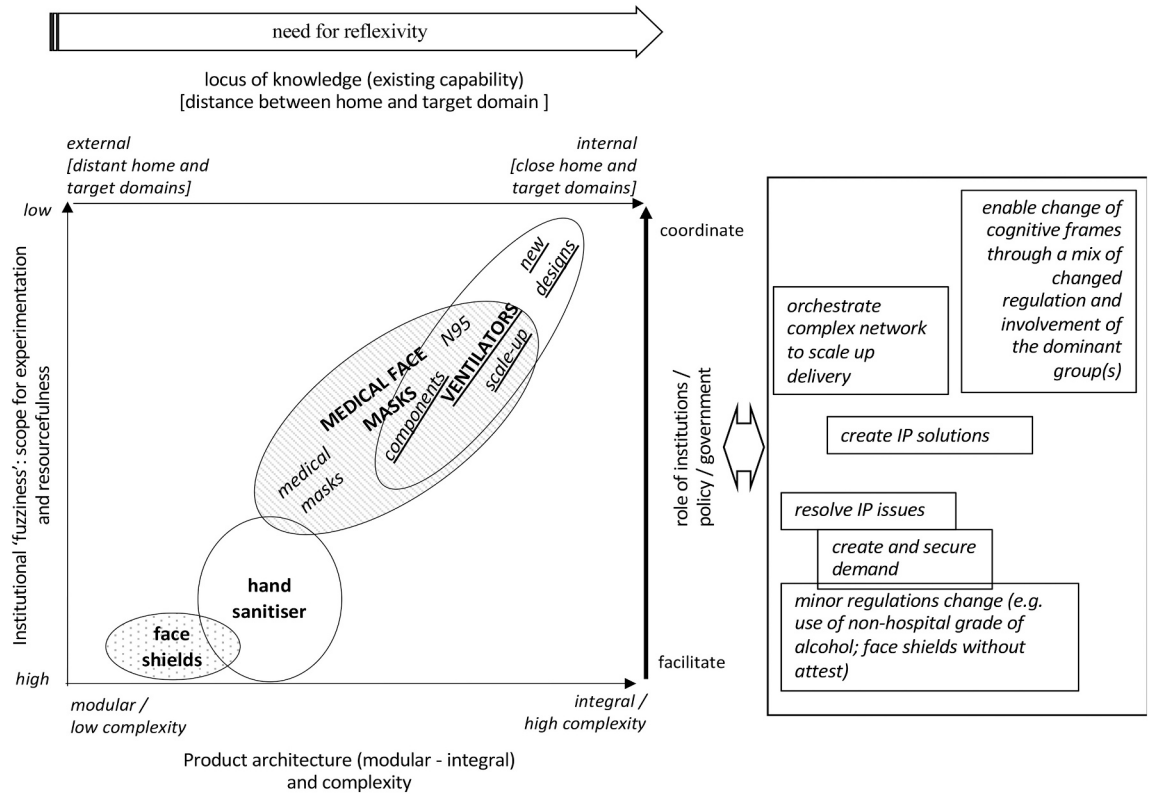

Fig. 4. Resourcing and product architecture: need for reflexivity and coordination.

development, the dynamics of interdisciplinary research collaborations, reflexivity and strategic management and decision-making.

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