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Elastic manufacturing: provisioning and deprovisioning production capacity to vary product volume and mix

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Abstract

Purpose – Advancements in responsive manufacturing have been supporting companies over the last few decades. However, manufacturers now operate in a context of continuous uncertainty. This research paper explores a mechanism where companies can "elastically" provision and deprovision their production capacity, to enable them in coping with repeated disruptions. Such a mechanism is facilitated by the imitability and substitutability of production resources.

Design/methodology/approach – An inductive study was conducted using Gioia methodology for this theory generation research. Respondents from 20 UK manufacturing companies across multiple industrial sectors reflected on their experience during COVID-19. Resource-based view and resource dependence theory were employed to analyse the manufacturers' use of internal and external production resources.

Findings – The study identifies elastic responses at four operational levels: production-line, factory, company and supply chain. Elastic responses that imposed variable-costs were particularly well-suited for coping with unforeseen disruptions. Further, the imitability and substitutability of manufacturers helped others produce alternate goods during the crisis.

Originality/value – While uniqueness of production capability helps manufacturers sustain competitive advantage against competitors during stable operations, imitability and substitutability are beneficial during a crisis. Successful manufacturing companies need to combine these two approaches to respond effectively to repeated disruptions in a context of ongoing uncertainties. The theoretical contribution is in characterising responsive

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manufacturing in terms of resource heterogeneity and resource homogeneity, with elastic resourcing as the underlying mechanism.

Keywords Just-in-case manufacturing, Resource heterogeneity, COVID-19, Flexible manufacturing, Cloud computing, RBV, RDT

Paper type Research paper

1. Introduction

In a world of increasing uncertainty and disruption, manufacturers must respond to supply and demand fluctuations in a timely fashion. Recent disruptions such as the COVID-19 pandemic, military conflicts, geopolitical trade tensions, natural disasters and cyber-attacks have interrupted the flow of material, information, labour and capital for manufacturing (Alexander *et al.*, 2022; Handfield *et al.*, 2020). Up to three quarters of manufacturing companies are vulnerable to such disruptions (Scholten *et al.*, 2020). Manufacturers must now strategise for upcoming and repeated disruptions.

Responsive manufacturing has been a popular research topic over the years; various concepts such as flexible manufacturing, reconfigurable manufacturing and cloud manufacturing have emerged to support manufacturers (Holweg, 2005; Koren and Shpitalni, 2010; Sarkis, 2001). These concepts aspire for efficiency, flexibility, just-in-time production and profit maximisation, simultaneously (Buer *et al.*, 2018; Shaaban and Darwish, 2016). However, manufacturers falter in protecting their consumers from epidemics, lockdowns, food price inflation, energy price fluctuations, trade conflicts and distant wars (Fajgelbaum and Khandelwal, 2022; Goolsbee and Syverson, 2021; Jaravel and O'Connell, 2020).

Some manufacturers did exhibit responsiveness during the pandemic, but not in a manner completely explained by theory, as argued below. Examples which garnered the most attention were of manufacturers who repurposed their production facilities to produce pandemic-related products, such as medical ventilators, face masks, face shields and hand sanitisers. This prompts three questions that merit clarification. Firstly, was the responsiveness challenge one of product novelty alone, or was there a volume challenge as well. Secondly, were these examples illustrating the concepts listed above. Thirdly and most importantly, this does not align with literature that advocates uniqueness of manufacturers. Resource-Based View (RBV), a prominent management theory, explains that manufacturing companies should make themselves so unique that they can neither be imitated nor substituted, and thus sustain competitive advantage over rivals (Barney, 1991). This is achieved through resource heterogeneity, where the company's resources are valuable, rare, inimitable and non-substitutable by its rivals (Ketokivi, 2016). However, during the COVID-19 pandemic, manufacturers were feted for violating the uniqueness of other companies – for producing medical ventilators, face shields, etc. without prior experience in those products. It would have been undesirable if major healthcare manufacturers had become so unique that other manufacturers were incapable of producing substitute devices. It is unclear if such imitation and substitution were stories of success for society, or a failure on the part of companies at becoming unique. Should companies such as GE and Philips be disappointed that they were so readily imitated and substituted for ventilator production during the pandemic? Is it desirable or undesirable when a manufacturer gets temporarily replaced during a disruption? The answer is relevant not only for the pandemic of the past, but also for trade tensions and military conflicts of the future. While RBV theorises about internal resources, many of these manufacturers utilised external resources, a phenomenon studied under Resource Dependence Theory (RDT) (Pfeffer and Salancik, 2003). Literature either focuses exclusively on internal resources (RBV) or external resources (RDT), neither of which can fully explain the phenomenon above. Previous calls to combine the two resourcing theories (Hitt *et al.*, 2016) fail to explicate how this changes our understanding of production resources for purposes such as responsive manufacturing.

This research explores how manufacturers responded to the COVID-19 pandemic. Since this was a temporary change in product output, the reallocation of production resources, if any, was also of interest. An idea in cloud manufacturing – which can be traced back to elastic computing – is of provisioning and deprovisioning resources to match computing capacity with demand. We explore a manufacturing analogy to understand how companies managed their product output during the pandemic. Stated more formally, this paper explores "*How can manufacturing companies provision and deprovision production capacity to vary product volume and mix?*" We adopt a theory generation research approach with the Gioia methodology. Twenty case studies of UK-based manufacturing companies were conducted, resulting in three key findings. Firstly, the study identifies elastic resourcing at four operational levels – production line, factory, company, and supply chain. Where different levels can achieve the same change in volume or mix, the decision trade-off by the manufacturer was studied. In such trade-offs, variable-cost-based responses were particularly well-suited for coping with unforeseen disruptions; this is our second finding. Our third and final finding pertains to resource heterogeneity and, as its opposite, resource homogeneity. Resource homogeneity helped manufacturers respond elastically to the COVID-challenge and manufacture pandemic-relevant products, while resource heterogeneity hindered manufacturers' ability to do so. We also formulate these findings into a framework.

Elastic manufacturing is the mechanism of provisioning and deprovisioning production resources by manufacturers, which was identified at various operational levels. The homogeneity of production resources facilitates such a mechanism. Our key theoretical contribution is on resource homogeneity for responsive manufacturing. While resource heterogeneity helps sustain competitive advantage against rivals, it can be detrimental during disruptions. With resource homogeneity, a manufacturer can redirect its production resources during a crisis. Elastic resourcing is facilitated by such homogeneity, where production resources are provisioned and deprovisioned between factories or companies. Such elastic resourcing enhances the responsiveness of manufacturers to disruptions. This theoretical contribution bridges the gap between RBV and RDT, while also explaining the real-world phenomenon witnessed during the pandemic. This leads to our key practitioner recommendation – a responsive manufacturer must strategise for resource heterogeneity during stable operations, and exploit resource homogeneity during crises. This could be the basis of "just-in-case" manufacturing for future disruptions. Further, the unit cost of a product is not the key criterion during a crisis (for example, medical ventilators during a pandemic, or ammunition during a war). A variable-cost-based response with a higher unit cost, as seen with elastic resourcing, can satisfy the need. Elastic resourcing leverages both resource homogeneity and variable-cost-based practices, to help manufacturers cope with future disruptions. We show that such a combination of homogeneous resources with variable costing will enhance productivity of the manufacturing system across both normal and disruptive periods.

2. Theoretical foundations

Various manufacturing concepts have been developed over recent decades to guide manufacturers in maintaining competitiveness through frequent and unpredictable market changes (Koren *et al.*, 2018; Santos Bernardes and Hanna, 2009). While these concepts have been popular in literature and practice, the pandemic revealed limits to what manufacturers can achieve through them. We collectively refer to these concepts as responsive manufacturing, our first theoretical foundation. Prominent among them are flexible manufacturing, reconfigurable manufacturing, and cloud manufacturing.

In order to analyse how manufacturers responded to the COVID-19 disruption, we adopt the perspective of resourcing theories, our second theoretical foundation. While *Resource-Based View* explains how manufacturers utilise internal resources to sustain competitive advantage, *Resource Dependence Theory* focuses on external resources that a manufacturer depends on and must maintain access to for their own business needs. Taken together, they help us study how manufacturers utilised production resources, both internal and external, to be responsive during the pandemic.

2.1 Responsive manufacturing

Extant concepts of responsive manufacturing have a common objective – to move away from rigid serial-production lines and towards operations that cope with demand variations and other environmental disruptions. However, they differ on various parameters, including the level of operation. Literature classifies operations into about six often overlapping levels – machine, cell, production line, factory, company, and supply chain (see examples Andersen *et al.*, 2015; Bi *et al.*, 2008; Yadav and Jayswal, 2018). Most concepts pertain to one or two levels, focussing on internal production resources, and emphasising product mix variation (as opposed to volume variation). Key exceptions are noted in the review below.

2.1.1 Flexible manufacturing. Flexible manufacturing is the most extensively developed concept under responsive manufacturing. At its broadest, flexibility is defined as the ability of a manufacturing system to cope with changing circumstances in the environment (Beach *et al.*, 2000; Mascarenhas, 1981). Flexible manufacturing conceptualises producing a variety of products from the same production system. Advancements have focussed on product mix – withstanding a certain level of variations in part styles, personalisation, and customisation without interruption to the production line (Kumar, 2008; Oke, 2005; Qin and Lu, 2021; Yadav and Jayswal, 2018). A long-running critique of flexible manufacturing is its unsatisfactory response to abrupt market fluctuations and major equipment failures (Koren and Shpitalni, 2010).

While research advancements in flexible manufacturing are most insightful at the intra-company levels (Duclos *et al.*, 2003; Yadav and Jayswal, 2018), its literature casts a wide net, describing flexibility of machine, process, capacity, product, routing, operation, production, and volume (Beach *et al.*, 2000). Supply chain flexibility overlaps with resilience literature (Stevenson and Spring, 2007). It encompasses supply base flexibility, labour flexibility, and order fulfilment flexibility (Tukamuhabwa *et al.*, 2015).

2.1.2 Reconfigurable manufacturing. Reconfigurable manufacturing has been defined in various ways (Bi *et al.*, 2008). The widely accepted conceptualisation of reconfigurable manufacturing is positioned halfway between dedicated serial-production lines and flexible manufacturing (Koren and Shpitalni, 2010; Koren, 2006; Koren *et al.*, 2018). While a dedicated serial-production line is rigged to manufacture one pre-defined part, a flexible manufacturing system can produce a vast variety of parts. However, reconfigurable manufacturing argues that such high levels of flexibility are unnecessary and uneconomical. A reconfigurable manufacturing system instead confines its options to a predefined part-family (Koren and Shpitalni, 2010). Production lines for different variants within the same product-family share machines and stations through the reconfiguring of assembly lines. This reconfiguring is limited to the shopfloor level, best illustrated in the rerouting of production lines to make variations in output (Bi *et al.*, 2008).

It has two key limitations. Firstly, the manufacturer must decide the family of parts (or products) that factory shall produce, and commit to the necessary capital investment up-front. Secondly, reconfigurable manufacturing still misses a bridge to business strategy (Koren *et al.*, 2018). Reconfigurable manufacturing is also confined to internal production resources of the company, and reconfiguring them to vary the product mix. Its application has primarily been for mix variation, rather than volume variation. Reconfigurable manufacturing is most insightful at the production line and factory levels of operation.

2.1.3 Cloud manufacturing. Cloud manufacturing builds on a foundation of cloud computing. Cloud computing provides on-demand access to a shared pool of computing resources which can be rapidly provisioned and released with minimal managerial effort (Mell and Grance, 2011). Its key characteristics are *Rapid elasticity*, *Resource pooling*, *On-demand self-service*, *Broad network access*, and *Measured service* (Mell and Grance, 2011).

Resource pooling (revisited in Section 5.3) is the practice where a provider-company accumulates its computing resources (memory, processing, and even network bandwidth) which are to be shared by multiple customers (Mell and Grance, 2011; Zhu *et al.*, 2021). A cloud computing provider operates a multi-tenant business model based on metered usage of this resource pool (Ojala and Tyrvainen, 2011; Ross and Blumenstein, 2013; Serrano *et al.*, 2015). For the recipient company, what would have been a fixed capital expenditure for an in-house server-farm now becomes a variable operating cost charged as a service (Bayrak *et al.*, 2011). Cloud computing rose in adoption during the pandemic (Aggarwal, 2021). We later revisit this elasticity of resources for a manufacturing analogy (Section 5.3).

Cloud manufacturing is a smart networked concept of responsive manufacturing that embraces cloud-based use of distributed IT and IoT resources (Ren *et al.*, 2017; Tao *et al.*, 2011; Zhang *et al.*, 2014). Centralised control of distributed resources (Xu, 2012) is complemented by the servitisation revenue model (Yli-Ojanperä *et al.*, 2019). These IT resources can be outside the legal boundary of the manufacturing company. Cloud manufacturing has primarily been about IT and IoT resources, with recent advancements focussing on blockchain and artificial intelligence (Li *et al.*, 2018; Ren *et al.*, 2017). These techniques are being applied for different manufacturing applications – process resilience improvements through data analytics (Fisher *et al.*, 2018), and supply chain visibility through information networking (Jassbi *et al.*, 2014) being two such examples. However, there has been little attention on production resources for manufacturing.

2.2 Resourcing theories

Theorising on production resources has been a popular topic in operations management (St. John *et al.*, 2001; Touboulic and Walker, 2015; Walker *et al.*, 2015). The two most prominent theories are Resource-Based View and Resource Dependence Theory. Given their contrasting emphases on internal resources and external resources, there have been calls to integrate the two in a complementary manner (Hitt *et al.*, 2016; Nandi *et al.*, 2020).

2.2.1 Resource-Based View. Resource-Based View is the most prominent theory used in manufacturing strategy (St. John *et al.*, 2001). It explains how companies sustain their competitive advantage against their rivals by managing their internal resources (Barney, 1991, 2001). Such sustained competitive advantage stems from resources being valuable, rare, inimitable and non-substitutable (Bromiley and Rau, 2016; Hitt *et al.*, 2016). This is referred to as the resource heterogeneity of the company, relative to other companies (Ketokivi, 2016). A company can appeal to its customers better if their resources are valuable and non-substitutable; and the company can outperform its rivals if its resources are rare and inimitable (Barney, 1991; Hitt *et al.*, 2016). Within manufacturing, RBV has been applied in four areas (Hitt *et al.*, 2016), operations strategy being the most relevant for this paper. Such RBV research has explored how operations resources can be bundles that achieve and sustain company-level competitive advantage (Hayes and Upton, 1998; St. John *et al.*, 2001). These resources can be process activities, information, and technology. While machinery, facilities and infrastructure can be considered RBV-resources (Nandi *et al.*, 2020), these can be easy for rivals to procure (Bromiley and Rau, 2016; Teece *et al.*, 1997). Instead, literature highlights company-specific resources like skills, knowledge and business process that are deeply embedded within the firm's organisational routines (Tranfield and Smith, 1998).

Competitive advantage is not to be confused with operational performance or financial performance of companies (Ketokivi, 2016). We later argue (in Section 5.2) that mere operational performance has its own merit during a crisis, without one-upmanship against rival companies elsewhere in the world.

2.2.2 Resource Dependence Theory. Resource Dependence Theory (RDT) is one of the most influential theories in organisation studies. It explains how organisations acquire and maintain access to external resources owned by other entities, upon which they depend for their operations (Pfeffer and Salancik, 2003). A company's success depends on how it manages these resource-interdependencies with other entities (Davis and Cobb, 2010). When corporations are vulnerable to uncertainties in their environment, they manage such interdependencies through power dynamics (Hillman *et al.*, 2009). RDT therefore studies the sources of power and dependence, and the tactics by which organisations reduce their uncertainty and dependence. RDT articulates the importance of the external resource to the company, the company's discretion or control over that resource, and the extent to which alternatives are available.

Within operations management, RDT explores power and autonomy between companies in a supply chain. It explains how a company can leverage the complementary resources of its chosen suppliers to enhance its own business performance (Jajja *et al.*, 2017). It helps understand the operational challenges and trade-offs that institutions face within their supply chains (Schnittfeld and Busch, 2016; Wontner *et al.*, 2020). It has been extended to understand the role of power on supplier flexibility (Liu *et al.*, 2022). In an uncertain environment, companies can buffer their own production core by accessing external resources when needed (Davis and Cobb, 2010). RDT tactics include – supplier contracting, strategic alliances, joint ventures, vertical integration, business diversification, excess production capacity, and worker cross-training (Davis and Cobb, 2010). These encompass the sharing of resources between companies, including knowledge.

The contrasting emphasis on internal resources in RBV and external resources in RDT is relevant for this paper. As shall be seen, we analyse manufacturers' COVID-responses as either utilising internal or external production resources. Additionally, the resource heterogeneity in RBV and – what we term – resource homogeneity as its opposite, are also relevant. If resource heterogeneity is the uniqueness of a company's resources, then resource homogeneity is the imitability and substitutability of one manufacturer's operational resources and production capability with those of other manufacturing companies.

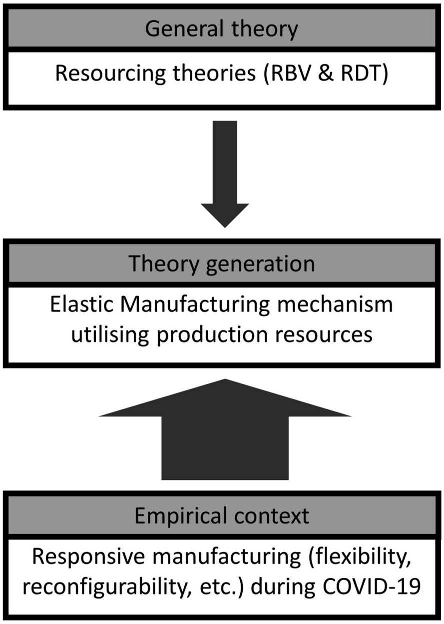
3. Research method

A qualitative inductive study was conducted to analyse the characteristics of elastic manufacturing responses, and how they enable operations in an uncertain environment.

3.1 Research approach

There are three methodological approaches to case research – theory generation, theory testing, and theory elaboration (Ketokivi and Choi, 2014), all three of which formulate theoretical insight. This research study adopts the theory generation methodological approach (Figure 1). Theory generation is the most common of the three. It relies more heavily on empirical evidence, and less on established theory, for formulating its theoretical insights through inductive reasoning. Theory generation is best suited when the contextual idiosyncrasies and the phenomenon are so unfamiliar that selecting a theory *a priori* would bias the research study and result in being theoretically conservative. While responsive manufacturing has been widely researched, in the judgement of the authors, the COVID-context and manufacturers shifting to pandemic-related products, were so unfamiliar that theory generation was the appropriate research approach. It still employs a theoretical perspective for data analysis, but the emphasis is on the empirical evidence gathered. Given its reliance on empirical evidence, theory generation research will be situationally grounded, but abstraction for generality is more challenging. Our generalisation of theoretical insights will be for other ongoing uncertainties and upcoming disruptions.

The Gioia methodology (Gioia *et al.*, 2013) is best suited for this type of theory generation. It is particularly strong for advancing conceptual novelty (Langley and Abdallah, 2011). It employs inductive reasoning while rigorously demonstrating connections between data and theory. This thematic analysis organises data into first and second order categories, ultimately leading to new concept development.



Source(s): Authors' own creation

Figure 1. Theory generation research approach

3.2 Research setting
The research setting is of the UK during the COVID-19 pandemic, and British manufacturing companies responding to the disruption. The pandemic was an unfamiliar context for the manufacturers, and our theory generation builds on a deep appreciation for the various idiosyncrasies of this context.

3.2.1 COVID-19 context. The COVID-19 pandemic impacted operations severely through supply shocks, demand shocks, workforce isolations, transport restrictions, and sporadic lockdowns (Handfield *et al.*, 2020; Shen and Sun, 2023). Many industries were severely affected, not least of which were tourism and healthcare. Manufacturing often operates in the background of these and other industries.

3.2.2 UK industrial context. The UK experienced three disruptions simultaneously. During the first wave of the COVID-19 pandemic, a national lockdown was implemented from March to May 2020. By December 2020, a vaccination programme has started, and most regional restrictions were lifted by mid-2021. A third wave was caused by the Delta variant of the virus, so named in May 2021. No lockdowns were imposed for Delta and subsequent variants; normalcy was gradually restored. A government furlough scheme protected manufacturing jobs from March 2020 to September 2021. The Brexit transition period from January to December 2020 was the second disruption. A Suez Canal obstruction (March 2021) also disrupted shipments to Europe from Asia, although to a lesser extent. The UK's production base has vaned in recent decades for high-volume low-profit-margin products. Local manufacturers (such as aerospace companies and Formula-1 racing teams) were pressed into action to cope with a lack of pandemic-related goods in the global marketplace. Britain's concerns for manufacturing sovereignty resonated with similar concerns globally.

We sought a diversity of British manufacturing cases illustrating product novelty and other changes (Table 1). Three broad trends were identified:

Change in output	Case	Company description	Operations during the pandemic
Product volume (increase)	Vol-Inc-1	A construction company (staff of about 550) that manufactures building products for roofing, pipes and building extrusions	Part of the increase in sales was due to people renovating their homes while staying at home
	Vol-Inc-2	A manufacturer of liquid and gas filtration solutions. It manufactures filters, filter capsules and filter housing	Experienced higher demand compare to pre-pandemic levels
	Vol-Inc-3	A manufacturer of electric motors and gearboxes. The company operates three manufacturing sites, two of which focus on machining and the third on assembly	Saw a 10% increase in volume demand, compared to pre-pandemic levels
	Vol-Inc-4	A manufacturer of sofas, with two factories in the UK and one factory in Lithuania, employing a few hundred workers at each site	Working-from-home motivated the purchase of more household seating
	Vol-Inc-5	A manufacturer of semiconductor capital equipment. Its customers are in semiconductor manufacturing, power electronics and LED devices	Experienced an increase in demand. However, coping with this increase was challenging due to a shortage in its own supplies
	Vol-Inc-6	Manufacturer of high-accuracy medical devices for blue-chip healthcare firms. Produces bone-screws and plates for orthopaedic, prosthetic and cardiac applications	Experienced a 20% "mild increase in orders based on pre-pandemic" demand
	Vol-Inc-7	A supplier in sporting goods that uses polymeric materials to make structural components for footwear	Experienced a decrease in demand during the initial months of the pandemic (early 2020), but has since experienced an increase in demand compared to pre-pandemic levels
	Vol-Inc-8	A manufacturer of cleanroom panels. About 85% of its orderbook is from the pharmaceutical sector, with other orders from general healthcare, tarpaulin covers for swimming pools, etc.	Increase in volume demand from its usual customers in the healthcare sector
	Vol-Inc-9	Manufacturer of roof systems and windows including fabricated roofing products, extensions, conservatory roofing and profiles for windows and doors	Increase in home renovation and home improvement during lockdown
	Vol-Inc-10	A manufacturer of shelving, racking and trolleys with customers in catering, healthcare, retail and industrials	Increased orders from healthcare customers
Product volume (decrease)	Vol-Dec-1	A high-end furniture manufacturer producing office-chairs, office sofas, tables and phone-booths	Sharp decline in demand for office-sofas and office-tables but subsequent increase in demand for phone-booth-style acoustic pods. Overall, the company has seen a decrease on its order-book
	Vol-Dec-2	Manufactures electronic materials, conductive paint and hardware for interactive projects sold as consumer kits. It recently expanded to smart facility applications, including touchless interfaces	An overall reduction in demand, with a variation within the mix
	Vol-Dec-3	Global producer of threads and yarns. They supply to make products such as airbags, tyres and medical sutures	Experienced an overall decrease in volume demand
	Vol-Dec-4	A manufacturer of water-efficient toilets for high-end commercial buildings and offices that are willing to pay a price-premium for conserving water	Reduction in demand attributed to many commercial buildings locked down during the pandemic

Table 1.
Case studies listed by output

(*continued*)

Change in output	Case	Company description	Operations during the pandemic
Product mix (new product)	Mix-New-1	A global alcoholic beverage manufacturer with about 200 brands and 8,000 employees globally	The UK division temporarily made tens of thousands of litres of hand sanitisers. The company has no intention of commercialising hand sanitisers
	Mix-New-2	A specialist-manufacturer in lamination and in rubber, foam and plastics converters. Half its orders are from the automotive sector, and remaining from packaging, construction, rail and healthcare	Repurposed its production facility to make face-visors. This new product has now been commercialised as a permanent offering
	Mix-New-3	A precision engineering company that primarily caters to the aerospace sector, with some clientele in defence and automotive sectors too. It produces plane parts and some components for cars	Helped the UK Ventilator Challenge. Outside of this UKVC participation, the company experienced a decrease in operation
	Mix-New-4	Works in automation. It invents new machines for production activities. Its clients are other manufacturing firms that need bespoke equipment for installation in their factories	Experienced a minor overall increase without any significant initial dip in demand. But the case is more insightful to analyse as a product-mix case because the company frequently reconfigures its production facility to make a novel machine for each new order
	Mix-New-5	A British flooring manufacturer in the construction industry	Made face shields as PPE during the pandemic
	Mix-New-6	A manufacturing clubhouse of about 400 members, with equipment such as laser cutters, 3D printers and lathes. The space is also occasionally used to host hackathons but had never produced goods for use by consumers	Used an opensource design (from USA) to produce 6,000 visors and masks for a local hospital, several GPs and care homes

Source(s): Authors' own creation

Table 1.

(1) *Work-from-home:* Staying at home increased demand for home renovations (as experienced by the construction sector), household furniture, and fitness goods. This decreased sales for office furniture, and goods used at social events.

(2) *Pandemic-related products:* A surge in demand from healthcare, which affected cleanroom panel producers, medical shelving, and filtration providers. Manufacturers outside healthcare temporarily shifted to making PPE, hand sanitisers, and medical ventilators. This often compensated for a decrease in demand from regular customers.

(3) *Trade restrictions:* As exporting-countries restricted shipping essential goods (e.g. healthcare), the UK government and industry pushed domestic manufacturers to innovate.

The reader can now appreciate why different companies (Table 2) even within the same sector experienced production demand differently; for example a sofa manufacturer (Vol-Inc-4) experienced an increase while an office furniture manufacturer experienced a decrease (Vol-Dec-1).

3.3 Data gathering

The data gathering occurred roughly one year since the start of the pandemic in the UK, the specific start date being unclear. Managers at twenty British manufacturing companies participated in this study through virtual interviews and discussions. All interviews were conducted over a two-month period from 12 May 2021 to 7 July 2021. The manufacturers represented in our study were operating in construction, furniture, plastic components,

Sector	Case	Company description	Interviewee description
Construction	Vol-Inc-1	Manufacturer of roofing, pipes and building extrusions	*Operations Manager* for less than an year, but an employee within the same company for 16 years
	Vol-Inc-9	Manufacturer of roof systems and windows and profiles for windows and doors	*Operations Director* for 3 years, within construction sector for about 20 years
	Mix-New-5	Flooring manufacturer	*Operations Director* for 1.5 years, over 27 years in manufacturing companies
Industrial goods	Vol-Inc-2	Manufacturer of liquid and gas filtration solutions	*Managing Director* for last 12 years, industry experience of over 32 years
	Vol-Inc-8	Manufacturer of cleanroom panels	*Engineering and Operations Director* for 5 years, industry experience of 15 years
	Vol-Inc-10	Manufacturer of trolleys	*Group Managing Director* for 4 years, with 14 years prior experience in supply chain and finance roles within manufacturing firms
	Vol-Dec-4	Manufacturer of high-end water-efficient toilets	*Operations Director* for 2 years, prior experience of 22 years in production, marketing and consulting
Electrical/ electronics	Vol-Inc-3	Manufacturer of electric motors and gearboxes	*Managing Director* for 3 months, within the company for 4 years, total of 18 years in manufacturing
	Vol-Inc-5	Manufacturer of semiconductor capital equipment	*President – Europe* at company
	Vol-Dec-2	Manufactures electronic materials sold as consumer kits	*COO and Co-Founder* for 13 years, after 3 years in design and project management
	Mix-New-4	Works in automation	*Managing Director* for 8 years, total of 28 years across engineering companies
Furniture	Vol-Inc-4	A manufacturer of sofas	*Director of Operations* for 14 years, industry experience of 32 years
	Vol-Dec-1	Office furniture manufacturer	*Operations Director* for 6 years, diverse engineering experiences across 30 years
Healthcare	Vol-Inc-6	Manufacturer of high-accuracy medical devices	*Owner* of company for about 39 years
Apparel	Vol-Inc-7	A supplier of sporting goods	*Head of Operations*, rising through ranks for 23 years in the same company
	Vol-Dec-3	Global producer of threads and yarns	*Manufacturing Director – Business Operations* for 1 year, within the company for 21 years
Food and beverage	Mix-New-1	Global alcoholic beverage manufacturer	*Head of Operations and VP Global Procurement* for 2 years, within the same industry for 24 years
Automotive	Mix-New-2	Specialist-manufacturer in lamination, rubber, etc.	*Commercial Director* for 3 years, with industry experience of 35 years
Aerospace	Mix-New-3	Precision engineering company	*Director* for 6 years, with varied managerial roles for 24 years
Recreation	Mix-New-6	Manufacturing clubhouse	One of the *Founders* in 2010, has held executive roles within the organisation since then

Source(s): Authors' own creation

Table 2.
Case studies listed by sector, with interviewee description

beverages, medical devices, footwear products, semiconductor production, synthetic fibres, and geared motors. We selected manufacturing companies from such diverse sectors and sizes to identify characteristics of elastic responses that were not specific to an industry.

Manufacturers were selected to maximise differentiation in terms of industry, organisation, internationalisation, and size.

The interviews were complemented by analysis of documentation and publicly available information about those manufacturers, where necessary for further clarification. Each semi-structured interview was scheduled for one hour (interview questionnaire in Appendix). The companies in this study have been anonymised and listed in Table 1. They have been categorised based on their production volume increase, production volume decrease, or change in product mix, relative to their pre-pandemic operations. The limited number of cases pertaining to product volume decrease is due to data saturation on that phenomenon. We have also included further details about the informants at these companies (Table 2) when categorised by sector. Such a listing shows that manufacturers in the same sector were affected differently.

3.4 Data analysis

We employed the Gioia methodology for data analysis and theory generation (Gioia *et al.*, 2013). Our data analysis consisted of three stages. First, open coding identified initial concepts in the data, which were then grouped into categories (Van Maanen, 1979). This first-order analysis started with informant-centric terms and codes. Where necessary, secondary source material was also used to triangulate our data to improve reliability. This data coding was a recursive rather than a linear process, with categorisations by the researchers, resulting in our first-order concepts. Secondly, these first-order concepts were refined and mapped on to the resource theories literature. These second-order themes are researcher-centric, and heavily informed by resourcing theories. Further, this attempt to map the evidence onto resourcing theories pointed to *elastic resourcing,* and the *trade-off* among multiple elastic resourcing options. The last aggregate dimension was regarding the use of *resources during uncertainty*. Finally, we used peer-debrief to confirm and refine the mapping of evidence through discussions between the interviewing authors and the other authors, thus employing the insider and outsider perspectives (Gioia *et al.*, 2013). This captured independent views of the themes, and also eliminated alternate explanations for the phenomenon studied. The data structure (Figure 2) is a graphical representation of our first-order concepts, second-order themes, and aggregate dimensions.

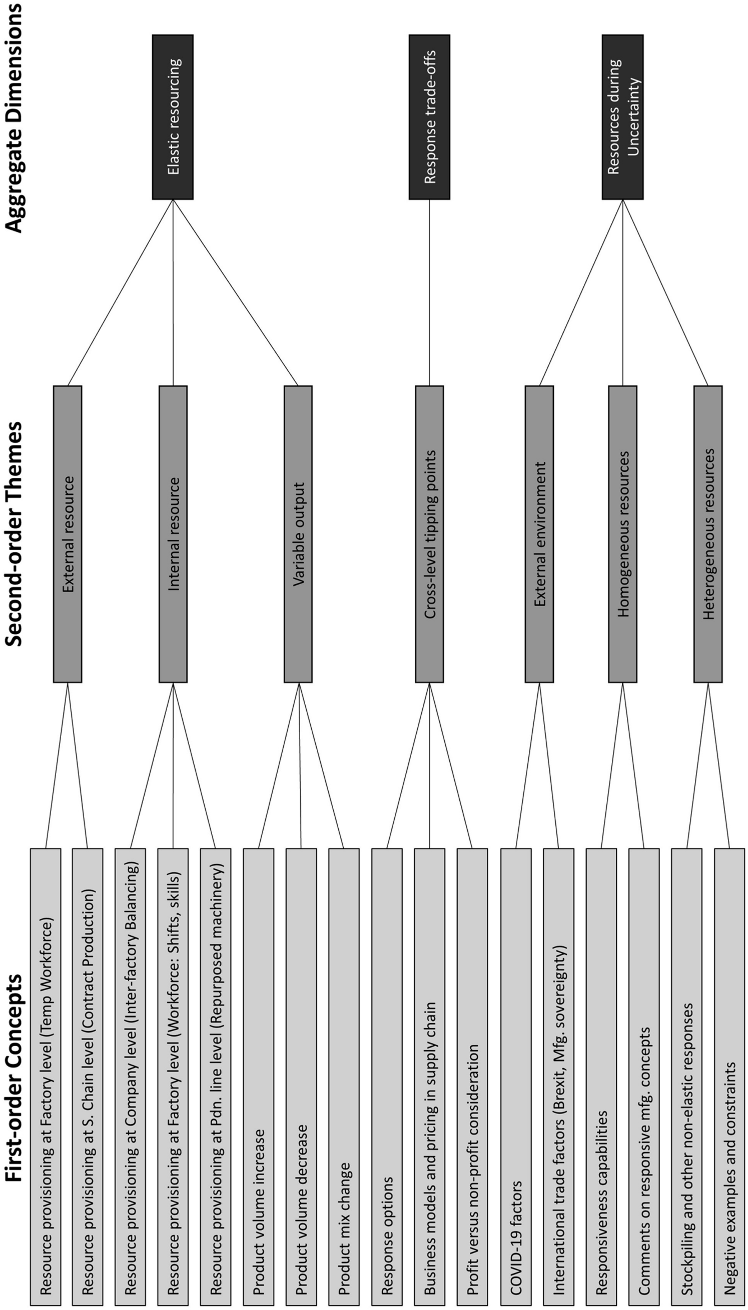
4. Findings

The findings from this study are structured as – elastic resourcing mechanism, the trade-offs that manufacturers face when comparing elastic response options, and the use of production resources for uncertainty.

4.1 Elastic resourcing

The study identified manufacturing responses at four operational levels (Table 3) where there was a provisioning and deprovisioning of production resources. We term this *elastic resourcing*, given its similarity to the cloud computing mechanism (Section 2.1.3). Some elastic responses are based on internal resources while others are based on external resources.

4.1.1 Supply chain level: contract production. A manufacturer can outsource some or all of its production to a different company, effectively commandeering that production capacity as an elastic resource for itself. Six manufacturers in this study were practicing contract production in some form. As explained by the respondent from Mix-New-1, partial-contract-production can vary product volume: *"I have got approximately 80% produced on [my firm's own] assets . . . and 20% is produced with partners, co-packers. And that creates this flexibility to change direction quickly."* The contract manufacturer operates as a pool of fungible assets for different clients.



Source(s): Authors' own creation

Figure 2.
Data structure

4.1.2 Company level: inter-factory balancing. Manufacturers that own multiple factories can redistribute the load to vary product volume and mix. When factories had comparable production capabilities, volume variation was feasible, as seen with Vol-Inc-8: *"… we're probably 100% out of [Site 1 factory], now 50% out of [Site 2 factory]. So we still got, you know, the idea is we'll be able to flex those …"*. The yarn manufacturer Vol-Dec-3 owns and operates two stages of factories, to vary product mix. The stage-1 factories are centralised and large-volume, producing generic grey thread. The stage-2 factories are distributed closer to customers, and customise through dying and coating the thread. The stage-2 factories were selectively locked down when demand reduced in those regions, thus varying product mix and total volume.

> We have factories closed at the moment, due to the second and third wave (of the pandemic) – and how we manage that is important – how we can change supply (flow between factories). Having a global offer (common for the first stage) where we make the same product in the same location, (makes it) very easy for us to switch demand between factories (in the second stage).

4.1.3 Factory level: elastic workforce. Elasticity with regard to workforce was identified in three ways: skill-diversification, temporary staffing, and shift-work. While skill-diversification enabled product mix changes, contract workers and shift-work pertained primarily to varying production volume.

Skill-diversification helps reassign employees to different product lines within a factory, as identified in Vol-Inc-3:*"skill diversification – having a workforce that is able to work on multiple different products … allows us to flex with the challenges …"*. Many manufacturers also resorted to additional shifts and overtime-work, which imposes a variable cost above the fixed-cost salary. Some manufacturers also relied on temporary staffing agencies to elastically alter their headcount, as seen in Vol-Inc-3:*"We have a very good percentage of temp-labour at any time … Historically, there has been a good 30% of the labour-force has been (sic) temporary labour. That has really allowed us to step-up and step-down as we need to. But those temps tend to stick with us three-months at a time."* Temporary workers are a variable cost for manufacturers while permanent-employees impose a fixed cost for salaries.

4.1.4 Production-line level: repurposed machinery. Some manufacturers redesigned their production lines to reassign existing machinery to different products or tasks. This was most evident from manufacturers who shifted to pandemic-relevant products. The Mix-New-2's executive explained shifting to PPEs as follows:

> Our manufacturing equipment … was idle (due to automotive sector stopping operations). So if we chose to make something (say) 25mm thick by 150mm long, then we could do that, couldn't we? So it was quite easy. If we wanted to put a programme in a digital cutter that would make a certain shape, we could do that.

Operational level	Elastic response	Resource location
Supply chain	Contract production	External
Company	Inter-factory balancing	Internal
Factory	Elastic workforce (skills, shifts, temp-staff)	- Skills: internal - Shifts: internal - Temp-staff: external
Production-line	Repurposed machinery	Internal

Source(s): Authors' own creation

Table 3. Elastic resourcing at different operational levels

4.2 Trade-offs in elastic manufacturing: moving from fixed cost to variable cost

Different elastic response options can deliver the same change in volume or mix (Table 4). Where there are options, there is comparison for trade-off. The study revealed that such trade-offs are highly contextual and preferences differ from one company to the next. Unsurprisingly, cost was a key factor in the choice of elastic response. More importantly, some manufacturers deliberately distinguished between fixed costs and variable costs. *Contract production*, *Temporary staffing*, and additional *Shift-work* impose variable costs. They preferred incurring a variable cost to tackle the occasional need for a variable output, as elaborated by Vol-Inc-7's executive, who coped with a temporary decrease in early 2020:

> . . . if the demand is fluctuating and not consistent, then . . . you want to turn that into a variable cost rather than a fixed cost. You don't want to be spending money on a machine, like a million dollars, and then find (that) you're only running it one day a week, . . . [instead] to be working day-in day-out and earning it's investment. . . . [During a temporary decrease in demand in early 2020] we took steps to try and remove fixed costs, where we couldn't replace those (fixed costs) with variable costs. [In an Asian country] A lot of people when they went back for the Spring Festival, . . . they just decided to stay at home . . . We didn't replace those people at that time, we relied on overtime, so that again, it became a variable cost rather than a fixed cost to us.

Elastic output	Appropriate elastic resourcing response(s)
Temporary change in product volume	Supply chain level: contract production Company level: inter-factory balancing Factory level: elastic workforce (shifts) Factory level: elastic workforce (temporary workers)
Temporary change in product mix	Company level: inter-factory balancing Factory level: elastic workforce (skill diversification) with production line level: repurposed machinery

Source(s): Authors' own creation

Table 4.
Elastic output from elastic resourcing options

4.3 Production resources during uncertainty

The study of production resources utilised by manufacturers helped understand resource homogeneity and heterogeneity during uncertainty.

4.3.1 Resource homogeneity. Some manufacturers exploited resource homogeneity to produce pandemic-relevant products such as medical ventilators, hand sanitisers, face masks, and face shields. Mix-New-3, a precision engineering company that participated in the UK Ventilator Challenge illustrated this as follows:

> . . . we didn't really have to look [for this production capability]; we juggle with jobs all the time, . . . we've got some brilliant, you know, operational people . . ., that's what they do. . . . I think the ventilator challenge was . . . we had to produce a couple of 1,000 components quickly. . . . that was no real hardship for us, because it's the sort of agile manufacturing that we're doing day to day anyway. . . . to do different sorts of work as we go on, but we've got to have that capability. . . . when people come to our factories, they kind of didn't realize you did this didn't realize you did all of this . . ..

Even under regular operations, imitability and substitutability between manufacturers have benefits. Although these companies can be in the same industry, Vol-Inc-9 respondent was comfortable that they had *"lined up a couple of other [manufacturers] in the same business industry that we said, if we, if we run out of capacity, they're happy to help . . .. "* Similarly, Vol-Inc-10's manager thought of such a manufacturer as *"a partner out in [a European country] who make very similar products to us and we have a good relationship with them who then help us out in that situation [of demand spike]."*

4.3.2 Resource heterogeneity. The strategic advantages of resource heterogeneity were proudly acknowledged by manufacturers. Vol-Inc-6's manager proudly explained why outsourcing was not feasible during high demand – *"With the highest quality machine-shop in the country? That isn't possible. . . . There's no one else at our level."* Similarly, Vol-Inc-2 was keen to maintain resource heterogeneity for its most important product lines – *"No real option to outsource – too specialised, really. . . . a lot of our processes, . . . are too specialised. There is no way we could subcontract to one of our competitors, which we wouldn't want to do!"*

Yet, manufacturers were also acknowledging the limitations of resource heterogeneity. A distant manufacturer may outperform on price during stable times but domestic production capability may be essential during a crisis. The executive from Mix-New-5 explained it best:

> And our biggest competitor in the UK is a company called [competitor], who do not manufacture in the UK. So they buy everything from the Far East and Asia. So they've been hit massively, . . . got the issues with factories backed up in [Asian country], . . . you have the shipping issues (due to Suez Canal obstruction in 2021). So we have won a lot of new business in a lot of different territories from our major competitor . . . as a direct result of the COVID crisis. You know, if your business model is you buy everything from the Far East, there's a risk there.

5. Discussion

This section articulates the shift in the global context of manufacturing, and elaborates our theoretical contributions to advance responsive manufacturing for this new context. The elastic manufacturing concept is then formally introduced.

5.1 Manufacturing in uncertain times

There has been a dramatic shift in the global context for industry (Table 5). In the *Before-COVID* (BC) context, many manufacturers prioritised high-value customers, meeting demand-side variations through product mix. High rates of global economic-growth were aligned with high-value consumerism and premium pricing for customisation. The *After-Delta* (AD) world is characterised by overlapping uncertainties such as war, lockdowns, trade tensions, inflation, and sporadic climate disruptions, collectively called "polycrisis" (Sorkin *et al.*, 2023). Ongoing supply uncertainties and inflation can raise prices (Ivanov and Dolgui, 2022; Lücker *et al.*, 2021) for manufacturers. Shortages of commodities (e.g. wheat from Ukraine, semiconductors from Taiwan) pose more of a volume challenge than a mix

	Before COVID-19	After Delta-variant	References
Demographic priority	High-value customers who demand personalisation and can pay a price-premium for instant gratification	Low-income households that seek staple goods at affordable prices during global inflation and economic slowdown	Sodhi *et al.* (2023)
Production priority	Just-in-time for customer gratification	Just-in-case of disruptions	Jiang *et al.* (2022)
Trade context	Globalisation and globalised supply chains	Post-globalisation and splintered supply chains (friend-shoring and near-shoring)	Rama Murthy *et al.* (2019)
Political priority	Trade deals to advance globalisation	Manufacturing sovereignty as preparation for international uncertainty	Handfield *et al.* (2020)

Source(s): Authors' own creation

Table 5. Shift in global context for responsive manufacturing

challenge. There is a need to rediscover the importance of product volume changes within responsive manufacturing. Reconfigurability of production lines, flexibility of machines, and design of supply chains – for product mix variation are not the same as for product volume variation. There is a need to revise manufacturing strategy for this sombre context of subdued downbeat expectations of industry and society.

5.2 Production resources for responsive manufacturing

In this study, we analysed production resources as either being formally within the company or outside it, thereby corresponding to either RBV or RDT. RBV and RDT may explain elastic responses (Table 3) in markedly different ways, but to a manufacturer, these are comparable alternatives for achieving the same change in output (Table 4). Therefore, there is a need for a coherent theorisation of production resources, to explain responsive manufacturing practices.

The emphasis in RBV was on resource heterogeneity, which was appropriate for one-upmanship in the BC-era marketplace. However, the challenge in the AD context includes uncertainties. Any manufacturer making themself irreplaceable is problematic for society and nation-states. For example, the imitability and substitutability of ventilator manufacturers and PPE producers was beneficial during COVID-19. Resource heterogeneity is needed for sustaining competitive advantage, but mere operational performance and financial viability can be achieved without resource heterogeneity (Ketokivi, 2016). During a crisis, operational and financial performance are more crucial than one-upmanship against a distant rival abroad who may no longer be able to supply anyway. Resource homogeneity is helpful in such a situation. Literature already questions whether operations resources can ever be made inimitable by others, despite the best efforts of companies (Bromiley and Rau, 2016). But we argue that resource homogeneity is desirable for manufacturing sovereignty during disruptions. This enters the remit of RDT. Companies must occasionally collaborate with other manufacturers including rivals for such responsiveness. Research in RDT has focussed on power and autonomy between companies that have each optimised for resource heterogeneity. There is now a need for studying power when managing homogenous resources.

The pandemic also revealed that unit-price becomes less relevant during a crisis. What was observed with PPE and medical ventilators could happen with ammunition during a war, or food during a famine. Unit-price optimisation has shaped strategies for competitive advantage and geographic dispersion of value chain activities. But if unit-price is not the key criterion during a crisis, then more expensive variable-cost-based responses become viable. Responsive manufacturing must accommodate such responses through underlying production resources.

There is a growing call to bridge the two major resourcing theories, RBV and RDT, for theoretical advancement (Hitt *et al.*, 2016). We answer this call by studying the use of both internal and external resources for responsive manufacturing, to provide comparable options for manufacturers. We bridge the two theories by focussing on resource heterogeneity and homogeneity. We identify the importance of resource homogeneity for responsive manufacturing, and the potential for variable-cost-based responses during disruptions. Our research therefore includes resource homogeneity when theorising production resources for responsive manufacturing. Articulating responsive manufacturing as a combination of resource homogeneity and resource heterogeneity can guide manufacturers to sustain competitive advantage during stable times and respond elastically to disruptions.

5.3 Elastic manufacturing

Elastic manufacturing paints a vision where manufacturers respond to disruptions by provisioning and deprovisioning a fungible pool of production resources. The crux of elastic manufacturing is the mechanism of provisioning and deprovisioning. This same mechanism recurs at various operational levels (Table 3). The ensuing elastic responses can be delineated according to the characteristics of production resources (Figure 3). These production resources could be located within the company or outside it, either unique to the company or imitable and substitutable by others. Those production resources which impose a variable cost of usage are particularly well-suited for responding to unforeseen disruptions. Homogeneous production assets operate as a fungible resource pool provisioned through metered usage paid for as a variable cost. Such a manufacturing strategy may require manufacturers to be homogeneous with their competitors for many production capabilities. Crucially, we caution manufacturers against external resources that can neither be imitated nor substituted for production capability, given the uncertainties of the After-Delta context.

	Internal Resources	***External Resources***
Homogeneous Resources	▪ Shift-work for elastic workforce (Variable cost) ▪ Repurposed machinery (Fixed cost) ▪ Inter-factory balancing (Fixed cost)	▪ Contract production (Variable cost) ▪ Temp-staff for elastic workforce (Variable cost)
Heterogeneous Resources	▪ Skill-diversification for elastic workforce (Fixed cost)	▪ [Relying on heterogeneous external resources can be disadvantageous during a crisis]

Source(s): Authors' own creation

Figure 3. Elastic resourcing framework

The elastic resourcing responses identified overlap with many existing concepts within responsive manufacturing (Table 6). This raises the question about the novelty of elastic manufacturing. Elastic manufacturing is fundamentally the mechanism of provisioning and deprovisioning production resources. At the machine or cell level, it is similar to flexible machines. At the production line level, it manifests as reconfigurable production lines. But at the supply chain level, it appears as supply chain configurations of flexibility or resilience. But when abstracted across operational levels, one can identify the same underlying mechanism adopted by manufacturers in responding to disruptions. Focussing on the mechanism, rather than fixing on a specific operational level (say, production line), helped us better explain the responsiveness of manufacturers during the pandemic. By recognising elastic resourcing as a key mechanism of responsive manufacturing, operations management research can explore ways of improving it. For example, this research identified that resource homogeneity facilitates such a mechanism of provision and deprovision better than resource heterogeneity does. Further, such a mechanism lends itself to metered usage for variable costing, variable cost being preferred by companies for unforeseen disruptions.

Elastic manufacturing response	Proximate theoretical foundation
Contract production	Supply chain management, supply chain flexibility
Inter-factory balancing	Distributed manufacturing
Elastic workforce	Labour economics, labour flexibility
Repurposed machinery	Flexible manufacturing, reconfigurable manufacturing

Source(s): Authors' own creation

Table 6. Elastic manufacturing responses and related theoretical foundations

There is an indelible imprint of cloud computing on elastic manufacturing – the provisioning and deprovisioning mechanism, resource pooling, and variable costs for metered usage. From the perspective of a recipient-manufacturer, contract producers (also called co-manufacturers) and temporary contract staffing agencies are resource pools in a manufacturing context. In inter-factory balancing, each factory views the other's production facility as a resource pool. Despite these commonalities with cloud computing, elastic manufacturing is not an extension of cloud manufacturing. Cloud manufacturing directly adopts computing tools to manufacturing applications (IT resources, blockchain, etc.). But elastic manufacturing adapts the tenets of cloud computing – elasticity, resource pooling, and variable cost for metered usage – to envision a manufacturing analogy.

6. Conclusion

Manufacturers can selectively provision production resources, at multiple operational levels, even across factories and companies. Such *elastic resourcing* can be – (1) *Contract production* at the supply chain level, (2) *Inter-factory balancing* at the company level, (3) *Elastic workforce* at factory level, which encompasses skill-diversification, temporary contract workers, and shift-work, and (4) *Repurposed machinery* at the production-line level. These *elastic resourcing* options present manufacturers with different pathways to achieve the same change in product volume or mix. Of these, variable-cost-based responses (*Contract production*, *Temporary staffing*, and *Shift-work*) are particularly well-suited for coping with unforeseen disruptions. Further, resource homogeneity can help manufacturers respond elastically, while resource heterogeneity can hinder their ability to do so. Elastic resourcing leverages both resource homogeneity and variable costing practices. A framework was formulated to encapsulate these findings.

6.1 Recommendations for practitioners

The various crises of the world (wars, trade conflicts, floods, etc.) effectively appear as production challenges of volume and mix upon manufacturing companies. In the context of supply disruptions and global inflation, more practitioner attention is needed on product volume changes within responsive manufacturing. This research offers three recommendations to practitioners. Firstly, manufacturers must understand the elastic resourcing options available to their company. Not all options (Figure 3) may be available to all manufacturers. Companies must analyse their manufacturing for fixed costs and variable costs. Variable-cost-based responses may increase the unit cost when occasionally utilised, but unit-cost is less relevant during a crisis.

Secondly, we argue that both buyers and suppliers can benefit through resource homogeneity. In light of ongoing supply chain "de-risking" (FT, 2023), resource homogeneity can enable manufacturing sovereignty. From a buyer's perspective, resource homogeneity of suppliers with each other (e.g. dual sourcing) and with the buyer (partial-contract-production in this study) is advantageous. But more provocatively, we argue that resource homogeneity is beneficial for foreign suppliers in securing buyers. It is preferable for a foreign supplier to say "Dear focal firm, we are not indispensable to you. You can easily replace us during a trade dispute or climate disruption. Your domestic manufacturers can quickly imitate and substitute us – you need not feel anxious in doing business with us. Further, our prices are most competitive." It would be less appealing if that foreign supplier argued "Our production capability is so unique that if a trade conflict breaks out between our countries, you shall find no alternative elsewhere in the world. Therefore, make us your exclusive supplier and become dependent upon us in the meantime."

Finally, we recommend that manufacturers should map resources for homogeneity and heterogeneity within their own supply chains and with other industrial sectors. Understanding resource heterogeneity will help prepare for responsiveness.

The responsive manufacturer of the future must strategise for sustained competitive advantage over rivals during stable operations (through resource heterogeneity), and offer functionality during crises (through resource homogeneity). This can help manufacturers prepare for just-in-case manufacturing, contributing to an overall increase in productivity across both normal and disruptive periods.

6.2 Theoretical contributions and future research directions

The paper makes three theoretical contributions, the first being resource homogeneity for responsive manufacturing. The research highlights that imitation and substitution of production capability, through homogenous resources, can enhance the responsiveness of manufacturers. Resource heterogeneity shall remain relevant for sustaining competitive advantage during stable periods, but homogeneity shall be advantageous during disruptions when mere operational functionality may suffice. Such resource homogeneity opens further opportunities for elastic resourcing (Figure 3).

Our second theoretical contribution is about resource heterogeneity for responsive manufacturing, particularly at the supply chain level. This study integrates RBV and RDT by focussing on resource heterogeneity for external resources. An analysis of resource heterogeneity (as theorised in RBV) is relevant even for non-competing companies within a supply chain, supply chains being the remit of RDT. Partial-contract-production (as identified in this study) is a good illustration of this. Dependence and power between companies, as studied under RDT, can be analysed through resource heterogeneity. More broadly, buyer-supplier relations need to be researched for resource homogeneity and heterogeneity, for responsive manufacturing.

Our third contribution is in identifying the recurring mechanism of elastic resourcing as key to responsive manufacturing during disruptions. It highlights how the same mechanism manifests differently at different operational levels, aligning with extant concepts such as flexible manufacturing, reconfigurable manufacturing, and so on. The paper characterises responsive manufacturing in terms of this resourcing mechanism, and the production resources that are provisioned elastically in this manner. Future research can therefore theorise responsive manufacturing in terms of resourcing mechanisms, and the characteristics of production resources that lend themselves to such mechanisms.

We recommend two future research directions for advancing responsive manufacturing. The first pertains to resource homogeneity between competing companies. We recommend employing an RBV-perspective to study the competition between firms that have similar production resources. We identified manufacturers who occasionally support their competitors during excess demand. Responsive manufacturing must theorise such phenomena better in terms of production resources. The second research direction pertains to the occasional cross-sector collaboration for responsive manufacturing. This study focussed on production resources, and we identify that homogeneity and heterogeneity are part of achieving such cross-sector collaboration. There is a need to develop just-in-case manufacturing strategies that are based on both resource heterogeneity and homogeneity.

6.2.1 Limitations. There are two major limitations in this research. Firstly, the data gathering was conducted remotely due to social-distancing rules at the time. Field visits would have captured details for machine and cell level changes; the current findings are therefore confined to higher operational levels (Table 3). The second limitation is regarding the generalisation of findings. The study was confined to British manufacturing companies, during a particular disruption. Generalising to other manufacturers elsewhere during future crises is difficult. It is only our speculation that crises such as military conflicts and climate events shall impose volume and mix challenges on manufacturers.

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Appendix
Semi-structured interview questionnaire

Introduction questions

(1) How has the pandemic affected your business? e.g. Have you experienced an increase/decrease in demand for your existing products? Have you pivoted to the production of PPE? How did you respond to the pandemic?

(2) What are the major constraints that you had to deal with?

(3) What have been your priorities through the pandemic?

Production responses and changes

(1) How was your production system/value chain affected by the pandemic? Which specific parts of your supply/value chain were impacted and how?

(2) How have you adapted your production system to respond to demand? (e.g. Did you acquire new resources? Did you establish new relationships for co-production? Did you redirect existing machines?)

(3) What has allowed you to adapt different aspects of your system? (e.g. specific capabilities, soft skills, etc) What were the main challenges involved in the adaptation?

(4) What has allowed you to quickly scale up (down) production if you had to do so? What were the main challenges involved in scaling up (down) production so quickly?

(5) What were the disruptions you experienced in the period (e.g. supply, human resources) and how did you adapt to those disruptions?

(6) How did this change your relationship with your suppliers and customers? Did you establish any new relationships?

(7) What were your cost considerations/implications?

(8) What other changes (internal or external) did you bring about as part of your response?

Post-pandemic business

(1) How will this experience affect your business in the long-term? Will you return to the production of your existing products if you pivoted to a new product, or have you incorporated the product into your portfolio?

(2) How has this changed your relationship with your suppliers and customers?

(3) Which other changes do you expect to retain? What do you think will revert back after the pandemic has subsided?

(4) Were any metrics useful when making these decisions? What metrics could have helped?

Concluding remarks

(1) Based on this pandemic-experience, what does resilience mean for your business?

(2) What has surprised you during this experience? Other learnings?

(3) Are you comfortable with us using this discussion for our research?

- We will share the article draft with you when it is prepared over the coming months

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