Elastic manufacturing systems: A system view on operations, firm, and supply chain resilience

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Abstract

'Black swan' events - such as military conflicts, pandemics, and semiconductor crises - drastically change product volume and mix patterns and shorten how long manufacturers have to cost-effectively respond to them. This is a particular challenge for highly regulated industries, such as aerospace, automotive and food manufacturing, where the regulations reduce agility. To inform the design of future manufacturing systems, this paper collects data from 29 industrial companies across these industries and uses thematic analysis. We derive business

needs and existing responses to demand change, integrate these codes and suggest a way of operation using three-level uncertainty buffering when demand constantly fluctuates.

Keywords: Resilience, Manufacturing, System dynamics

Introduction

The COVID-19 outbreak amplified the need for medical equipment (e.g., masks, sanitisers) and reduced demand for other products (e.g., alcohol batch distilling for the hospitality sector). While some firms reacted to the demand changes by reconfiguring their production (e.g., from whiskey to sanitiser) (Murthy, 2023), more complex products, such as healthcare ventilators, have shown the failure of traditional models of supply chain resilience. For example, to satisfy the demand for ventilators at the beginning of the pandemic, the UK government had to initiate consortia across industries around the ventilator as a product (Cabinet Office, 2020; Liu et al., 2022; von Behr et al., 2022). In VUCA[1] environments, where uncertainty and demand fluctuation are common, rather than an exception (and government support is an exception, rather than common), firms need a holistic system view to match their production with the customer demand change as closely as possible, considering firm, factory, and supply chain levels of operation.

In business and management research, resilience is understood as an ability of a firm to sustain profitability. Offshoring production to low-cost production regions makes a firm vulnerable during demand change periods (Roscoe et al., 2022). In operations research, resilience is often connected to flexibility, i.e., coping with changing circumstances in the environment (Beach et al., 2000; Mascarenhas, 1981) or reconfigurability - i.e, the ability to produce a variety of products (mix) using the same product lines (Koren and Shpitalni, 2010). Factories optimise scheduling systems for a demand level to optimise the unit costs of production. In supply chain research, resilience is linked to sensing and responding to demand change (Vanpoucke & Ellis, 2019). The response can comprise a combination of principles: the need for design; collaborative working; the need to be agile; the need to create a risk management culture (Christopher & Peck, 2004).

Although the existing literature extensively studies the means to recover at the individual firm, factory, and supply chain levels, their interconnection is still under investigation. Moreover, there is a lack of studies that go beyond demand recovery and consider the operation of supply systems under constant demand fluctuation and risks of demand shocks. Thompson et al. (1967) argued that all organisations need to 'buffer environmental influences', but still, it is unclear how to do it with current complex production systems, particularly with supply chains stretched towards low-cost production regions. First, there is a lack of studies on whether the firm's needs for resilience overlap with supply chain or factory needs. Second, it is unclear how more than one level of responses may be aggregated. Third, resilience is not analysed as a system of responses across the three levels. Figure 1 demonstrates our conceptualisation of demand volume/mix changes along the firm, factory, and supply chain levels.

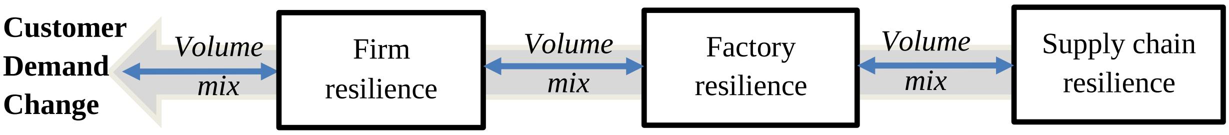

Figure 1– Conceptual model of the paper

Our research questions are: *what are the current business needs due to product volume/mix change at the firm, factory and supply chain levels? What are the available responses to address these needs?*

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[1] Volatile, uncertain, complex, and ambiguous

In response, we contacted 29 industrial companies in four countries and discussed their business challenges during product volume/mix changes and their responses to overcome the negative consequences. We build on Hopp and Spearman (2011) original idea that any system with variable demand would have to buffer that variability with inventory (i.e., safety stocks), capacity (i.e., idle production lines), and/or lead time of resource provision (i.e., producing closer to customers). Using the sample, we derive each level's business needs and responses, and create the integrated framework of uncertainty buffering for a manufacturing system. By so doing, we go beyond the literature on resilience that focuses on disruption recovery (Christopher & Peck, 2004; Wieland & Durach, 2021). Instead, we argue that firms can employ *a new systems-level modus operandi* for the environments when demand constantly fluctuates. We contribute to designing the next-generation Elastic Manufacturing Systems (EMS), which will scale output quickly and cost-effectively by provisioning and de-provisioning resources[2,3]. EMS will use buffers across factory, firm, and supply chain levels to provide optional solutions to demand change, which can comprise a combination of responses at different levels.

The remainder of this paper is structured as follows. First, we introduce the thematic background. Second, we describe our qualitative research methodology, and after that, we present and discuss results against the literature. Finally, we conclude with the limitations and future research directions.

Literature review

Firm resilience

In the economic literature, demand fluctuations are sudden events that temporarily increase the demand for goods and require resource provision. These can prevent a firm from serving its customers and/or lower profitability during these periods due to the increased costs of material, human, and financial resources (Olaogbebikan & Oloruntoba, 2019). Resilience is understood as an ability of a firm to sustain profitability during these demand change periods. Firms often offshore production to become more cost-efficient but reduce flexibility and transparency, vital during demand change (Roscoe et al., 2022). Digital technologies support resilience by creating visibility for companies within the value chain to access extra capacities (Ellis, 2021). The literature on resilience suggests that firms may engage in demand-driven collaborations to access these capacity options (Wu et al., 2005). For example, firms can enable a multi-sourcing strategy for critical resources by switching between in-house production and supply networks. Toyota introduced shadow suppliers along their supply chains to achieve this (Hettich & Kreutzer, 2021).

Factory resilience

In operations research, resilience is often referred to as *flexibility*, as an ability of a manufacturing system to cope with changing circumstances in the environment (Beach et al., 2000; Mascarenhas, 1981) or *Reconfigurability,* as the ability of production lines to share the same machinery for a predefined product family (Koren & Shpitalni, 2010). Both features of resilience at the factory level have limitations: Flexibility is highly costly, yet cannot respond satisfactorily to supply disruptions (Koren, 2006). Reconfigurability is tightly coupled for a product family, which implies a capital investment up-front, with fewer links to the business strategy (Koren et al., 2018). To a large extent, the known responses for shop floor resilience remain limited to stockpiling semi-parts or idle parts of production lines.

Supply chain resilience

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[2] https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/T024429/1 (accessed 19.04.2023)

[3] https://gtr.ukri.org/projects?ref=EP%2FT024429%2F1 (accessed 17.01.2023)

Companies consider responsiveness and cost-efficiency as traditional trade-offs when designing the resilience of their supply chains (Fisher, 1979). Resilience is an essential supply chain characteristic, helping 'to absorb adverse external turbulences and bring back the normal conditions' (Hosseini et al., 2022; Kumar et al., 2022). From early 2010, digitalisation has emerged as a significant moderator of this trade-off 'from the moment an order is placed right through to outbound logistics' (Kagermann et al., 2013). Information sharing along the supply chain tiers improves situation awareness (Overby et al., 2006), their causes, and reaction times (Brandon-Jones et al., 2014). Creating supply chain resilience requires multiple actions: 'redesigning supply chains, collaborative work, agility, and a risk management culture' (Christopher & Peck, 2004). For example, German textile manufacturers re-used materials from other production to manufacture face masks during the Covid-19 pandemic (Mueller et al., 2021).

Contribution area: resilience across three levels

After Thompson et al. (1967) argued that all organisations need to 'buffer environmental [uncertainty] influences', and Hopp and Spearman (2011) suggested the idea that any system with variable demand would have to buffer that variability with inventory (i.e., safety stocks of products), capacity (i.e., idle production lines), or lead time of resource provision (i.e., producing closer to customers), this paper builds up on the concept of uncertainty buffering at the operations of a firm, factory and supply chain. In contrast to the resilience literature focusing only on disruption recovery (Christopher & Peck, 2004; Wieland & Durach, 2021), we argue that firms must learn how to operate during permanent demand fluctuations, using three buffers to demand uncertainty at three levels. Early works, e.g., (Sodhi & Tang, 2023), consider inventory capacity and capability to mitigate the uncertainty of demand. However, a systematic investigation of business needs and available responses to product volume/mix changes is missing.

Methodology

We collected qualitative data from 29 leading industrial companies that faced product volume/mix change during the last five years and attempted to respond to it. We used thematic analysis (Braun & Clarke, 2006), a robust six-step procedure for inductive data comparison and coding, to derive reproducible findings from data. This method allows for less observer bias due to several coders and provides a rich understanding of a complex phenomenon by comparing the codes between the firms.

First, we look at the business needs to demand volume and mix changes, how companies respond to them, and at which level (firm, factory, or supply chain) these responses happen. We agreed on including new sub-categories and links as they appeared in the data (King & Horrocks, 2010). Inter-coder reliability was ensured by following an iterative process for analysing content using three coders (Creswell & Miller, 2010), and any misalignments in the coding was resolved through discussion (Kassarjian, 1977).

Second, the first coder integrated the codes into the Gioia framework(Gioia et al., 2013), using three-level uncertainty buffering as a backbone Figure 2.

Third, based on the results of the thematic analysis, we integrate the conceptual model of the paper (Figure 1) with the findings (Figure 2), thus deriving an integrated framework for systematic uncertainty buffering (Figure 3). We followed the abductive procedure of (Dubois & Gadde, 2002), i.e., simultaneously evolving the theoretical framework, empirical fieldwork, and case analysis. By mapping the links between the needs and responses at the systems level, we suggest ways to operate under volume and mix disruptions when demand changes. External validity was ensured by reviewing previous literature on uncertainty buffering, thus removing the observer bias (Eisenhardt & Graebner, 2007).

Findings

Our data reveal business needs and existing responses for uncertainty buffering at firm, factory, and supply chain levels. This section describes the three critical issues shared across companies: *business needs* related to demand fluctuation and the *existing responses* to absorbing volume/mix change at each level.

Firm-level uncertainty buffering

The firms need *customers' commitment* to smooth the irregularity and mix of their purchases (21/29), and *external communication* (8/29) is a feasible way to do so.
Business need: The respondents mention the need to react to massive volume/mix changes as a result of last-minute promotion campaigns and seasonal variations (IP6)[4]. Since firms react to highly specific or unusual requirements (IP16) that often come unexpectedly (IP18) it causes business models to become less profitable (IP5, IP10, IP14) and calls for customer negotiation.
Response: Sharing the demand fluctuation concerns with customers will likely smooth their demand pattern (IP15). For example, IP21 suggests that firms can 'negotiate with customers to postpone delivering certain batches'. Alternatively, IP19 suggests 'passing [extra] costs to customers', but only after informing them about the temporary issue of price fluctuation. If customers accept the open nature of price fluctuation, it can help support manufacturing firms' operations. IP20 says, 'if a customer fails to accept an increase in cost [due to the lower demand, we] temporarily shut down part of the plant.'

The firms need supplier commitment (8/29) to increase the number of guaranteed deliveries on demand, where balancing *suppliers* (6/29) is a likely response.
Business need: Firms ask: 'How to achieve assurance of supply?' (IP7) and 'How to ensure suppliers deliver unless you own them?' (IP14). Suppliers often provide parts 'which are not in tolerance, despite being provided with certification that says they should be' (IP12). Strengthening relationships with the supplier network can increase the quality of these supplies and enable minimum quantity orders on demand (IP28). Further, firms need modularising of complex functional components to increase supply from subcontractors. IP23 suggests that firms must 'design products ready for disassembly' and decompose unsold products for assembling new orders.
Response: The largest furniture manufacturer uses a principle of differentiated factories: low-volume production with predicted demand vs small-volume production with unpredicted demand (IP13). In the event of demand fluctuation, the firm may switch to another plant (IP29). Alternatively, 'large volumes [can be] produced in low-wage countries and sent for further customisation next to customers'– IP28. The unit costs should not be the only criteria for supply chain design but the potential demand structure (IP2). If managers are driven by costs only, it leads to what IP20 names 'crazy flows [i.e., illogical, superfluous material transfer links]' between the plants, raising supply chain complexity and reducing transparency. IP23 suggests the priority should always be to source and sell in the same region, which also benefits from supply chain synchronisation (i.e., bridging operations, processes and people) '.

The firms require *safety stocks* (8/29) and *a new business model* (6/29) to cover these costs.
Business need: The leading technology provider of manufacturing equipment (IP25) confirms the operation under the unpredictability of demand. Hence, firms need to prepare and respond (IP24) by planning reactions to risks (IP23). IP17 suggested capturing specific demand change patterns to respond better. For example, '[their] demand increases up to 7% annually coupled with daily fluctuations'. As an 'increase of production variety reduces safety stock' (IP2, IP6), the firms must hold inventories along value chains based on risk levels.

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[4] Individual Participant

Response: The new systems-level business model should focus on resilience as a critical consideration rather than cost-efficiency alone. For example, a large industrial company (IP23) reveals that they have locked CAPEX to ensure duplication in capacity and skills up to 8%. IP13 suggests calculating what a firm would lose 'if the risk X happens'[5]. By knowing the risk implications, large firms can motivate their risk-averse suppliers, indirectly increasing resilience for everybody in the value chain. For example, there must be a systems-based decision of who pays for operating inventories and other cost-intensive drivers of resilience. Like insurance policies, the active contributors to systems-level resilience must be supported with a premium, whereas other related partners share the costs. IP29 suggests a new value proposition for such a business model - the speed of response, i.e., those who pay extra will get supply quicker.

Factory-level uncertainty buffering

The factories need *quick machine allocation* (9/29), which requires novel *technologies* (20/29).
Business need: The factories of the largest European manufacturing company (IP25) need to produce 'a high variability product within a short lead time' and 'make a range of very different products' (IP25). For this purpose, factories need to 're-allocate machines [that are currently] highly calibrated for specific jobs' (IP11). It is 'cost-non efficient to produce in small volumes due to extra costs on cleaning the line' – IP18, therefore there is a need to speed up changeover. IP16 confirms that changeover is time-consuming, e.g.,: 'Low-batch manufacturing is highly dependent on set up times', so we must calculate timings for machine allocation(IP21).
Response: Digital technologies provide new ways to 'reduce time to clean equipment, and adapt to changes over time' - IP18. New tools 'automatise some parts of production which were previously done manually' (IP8, IP21) and scale the capacity of plants to provide that product' (IP29). IP16 suggests creating an app that allows shop-floor workers to track the set-up times and relate them to jobs.

The factories need *quick worker allocation* (8/29), which requires *team commitment* (5/29).
Business need: Delays are likely when 'the number of subcontractors becomes critical' (IP14) and call for improving coordination at shop-floor (IP8). IP11 adds that 'production [often becomes] idle; [and] we have nothing to work with'. IP18 claims that additional delays are brought by production errors that stop the process and require inspector involvement.
Response: IP23 recommends making assembly workers active by upskilling and 'looking after the morale of teams' (IP8). IP10 further builds upon moving responsibility towards the workers, i.e., by 'making [more] people responsible for small building blocks'. In addition, experienced workers can identify new process changes as needed (IP12) and coordinate work allocation.

W*ork-in-progress management* needs (6/29) can be supported by *repurposed assets* (7/29).
Business need: There is a clear need to improve work-in-progress (WIP) and storage management during demand fluctuation (IP8). A 'high capital cost plant not running makes leaving assets idle very unattractive; ability to switch plant off/on is quite difficult'- IP19. IP26 adds that 'if there is no right scheduling - [we] have to recycle materials and (the lack of) physical space becomes a problem', also confirmed by IP17. IP3 mentions that missing key people ‘with a high knowledge of the process (e.g., specific welding)’ leads to inefficiencies.
Response: Repurposed assets include re-using skills from other plants when demand spikes (IP29), short-term shop-floor layouts with manual tracking and/job cards, and relying on workers' expertise (IP22). For example, IP3 uses a resource marketplace across sectors to target workers with specific capabilities. Repurposed assets also can compensate for the high energy costs. For example, IP21 uses the heat of by-product compressors to heat the production halls.

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[5] IP13 compared the resilience drivers with brigades of firefighters that reduce risks in the case of fire.

Supply chain level to uncertainty buffering

Supply chains need *multi-sourcing* (5/29) and can try *supply chain refactoring* (18/29).
Business need: Firms agree that there is a need for multiple suppliers as the global business environment is unpredictable due to geopolitical risks (e.g., the leading furniture manufacturer - IP13). The leading UK car manufacturer claims: 'Resilience to demand changes requires multi-sourcing to ensure capacity, but CAPEX is high' (IP20). Likewise, the electronics manufacturer in Poland (IP21) felt 'a sudden stop in production in one firm branch in Ukraine' due to the military conflict and struggled to find an alternative supplier.
Response: Finding as many suppliers as possible (IP10) increases the optionality of potential choice. Furthermore, early supplier involvement can help to develop a supplier pool (IP20, IP25) and regionalise the production of components (IP7). IP23 mentions that it can shorten supply chains and reduce complexity by bundling factories for 'Make-Pack-Test processes'. IP15 argues for further redesigning components, e.g., 'using one large chip instead of multiple chips' and defining 'technology nodes [e.g., microchips that] can be used in TVs and cars'.

Supply chains require *on-demand parts provision* (20/29) and *short-term contracts* (7/29).
Business need: Respondents mention the need to provision resources on demand quickly, which is challenging if outsourcing is too far away. For example, the slow supply of raw materials (IP29) can cause a bottleneck in emergency production. In the recent pandemic, the liquid for sanitisers was available, yet it was challenging to source the packaging bottles quickly (IP4). Local supply firms need to sustain quality levels and be ready for the potential contract (IP9).
Response: Supplier development of potential local partners can play a positive role. For example, the Chinese platform textile manufacturer (IP28) builds trustworthy relationships with a network of regional factories and sources small volumes of garments (up to 500). By testing the market and analysing data on sales performance, they can adjust production and gain agility, removing the need to outsource large-volume production (IP29).

Supply chains require new *regulation* (12/29) that enables re-using components from other sectors, and *information sharing* (8/29) across supply chains can inform how the parts are made.
Business need: Respondents mention the need for regulation alignment to allow supply from alternative supply chains (IP2, IP24). For example, aerospace and automotive companies typically have various regulatory requirements across the countries producing semi-parts (IP3, as there are differences in manufacturing processes across geographical locations/sites, and different process characteristics' (IP9). IP5 adds that 'resources in healthcare are [even] less likely to be replaced', e.g., due to high contamination requirements (IP2). IP10 mentions a 'need for certification, recertification' due to 'a growing catalogue of spares' and a high 'cost of [supply chain] complexity' (IP9). Finally, IP23 suggests the need for on-demand resource provision by regulating supply chains as an integrated system (IP20).
Response: IP23 suggests 'supplier-customer data integration' and 'exploiting [this] information to activate [new] supply chain designs'. Batch tracking supports pooling data together (IP2) to monitor a predefined list of components' life-cycle. IP23 suggests 'granting certificates ensuring compliance with resilience' to incentive firms to increase the number of available sources and their capacity to deliver on time.

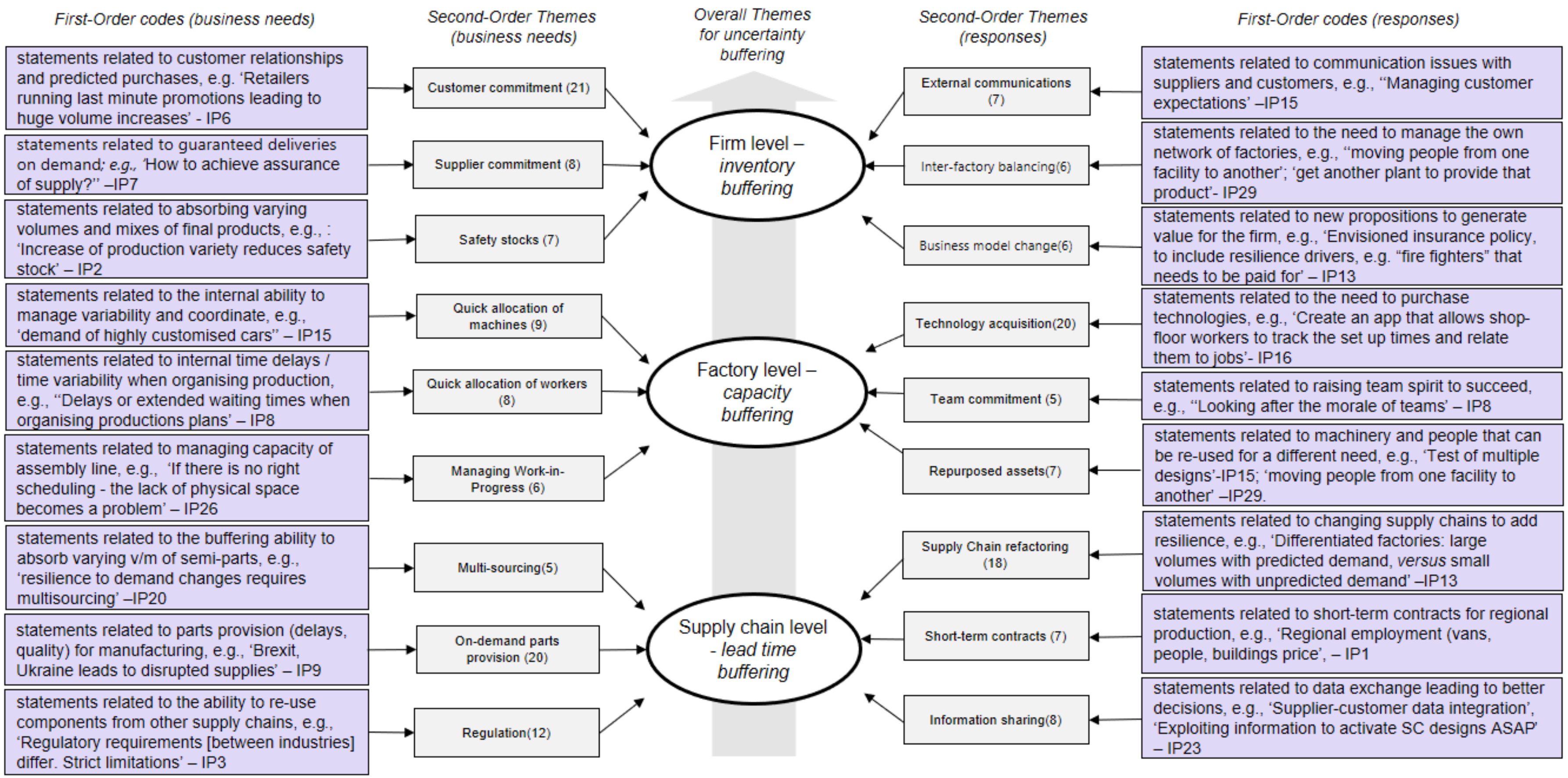

Figure 2 – Thematic Analysis (three most critical business needs & responses)

Discussion and Contribution

The data shows the *business needs* and *responses* to product volume/mix change at firm, factory, and supply chain levels. We position the business needs as requirements for manufacturing systems to operate under demand fluctuation, while the existing responses provide evidence to create solutions at three levels. Thus, the levels become *buffers against environmental uncertainty* (Hopp & Spearman, 2011; Thompson et al., 1967), Figure 3.

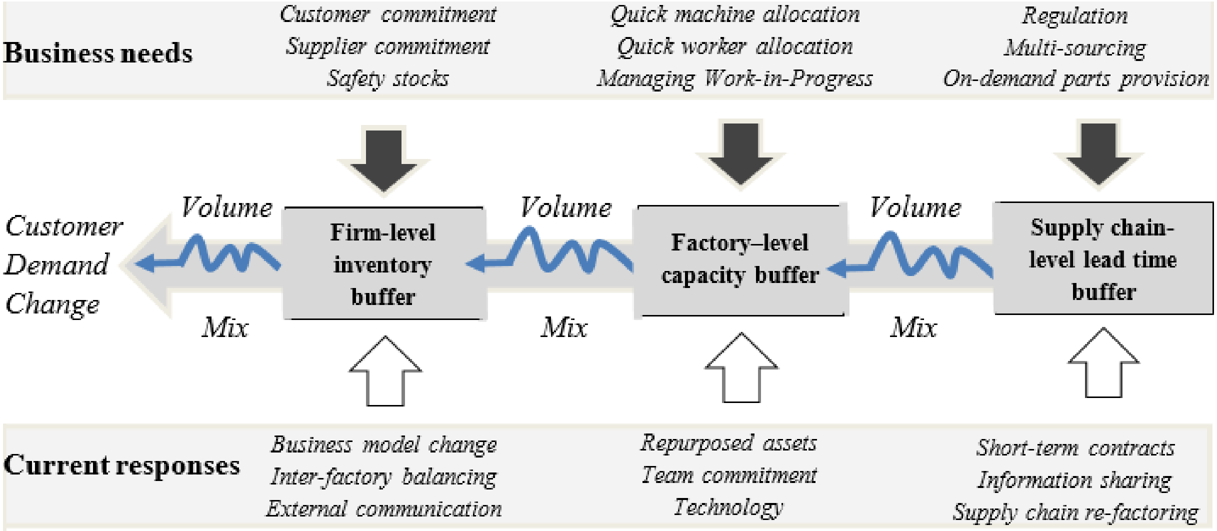

Figure 3 – Integrated framework for system view on resilience

This study extends the current theories of industrial resilience, which are predominantly focused on recovery, e.g., (Christopher & Peck, 2004; Wieland & Durach, 2021). Although a conventional manufacturing system may have lower unit costs, this comes from accepting the demand change risks. Building uncertainty buffers at the three levels may raise unit costs, but in return, the manufacturing system gains the ability to operate under demand fluctuations and satisfy customer demand. Managers can use the outcomes of this study to prepare their firms for operation in the VUCA[6] world. First, strengthening customer and supplier relationships at the firm level opens up the issues of volume and mix change and smooths demand patterns. Second, adding new technologies and improving access to skilled workers across factories increases the visibility of resources and capacity sharing across supply chains. Third, developing regional suppliers supports local on-demand resource provision.

Future research will explore how response at one level may impact others. It is still unclear what are the solutions for a specific business need across the levels and what are the time limits and the costs for responses. For example, to what extent do companies respond through various levels to a given disruption, and what are the challenges if they are not doing it? What are existing cross-level responses? The answers to these questions will show how to make manufacturing systems elastic to demand fluctiation.

Acknowledgements

The first author acknowledges the role of funding that helped to support this research: the EPSRC funding, grant reference EP/T024429/1 via ‘Elastic Manufacturing systems - a platform for dynamic, resilient and cost-effective manufacturing services’ and the ESRC Made Smarter Network+ ('InterAct') Commissioned Research Programme, Early Career Researcher Fellowship number J17293/ES/W007231/1. Personal thanks to Prof. Jag Srai and their team for organising the annual Cambridge International Manufacturing Symposium 2022 that facilitated data collection for this paper.

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[6] Volatile, uncertain, complex, and ambiguous

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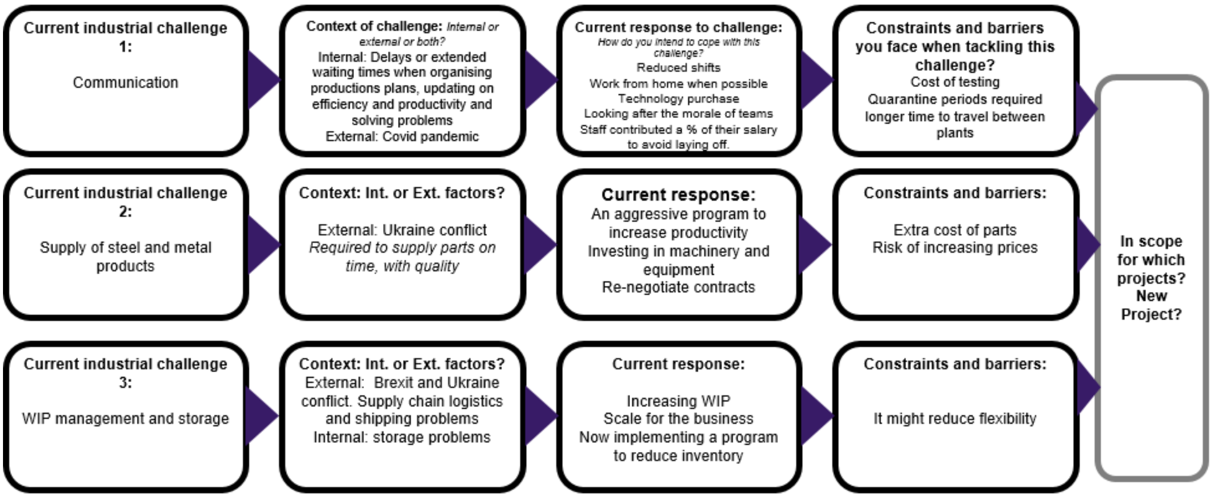
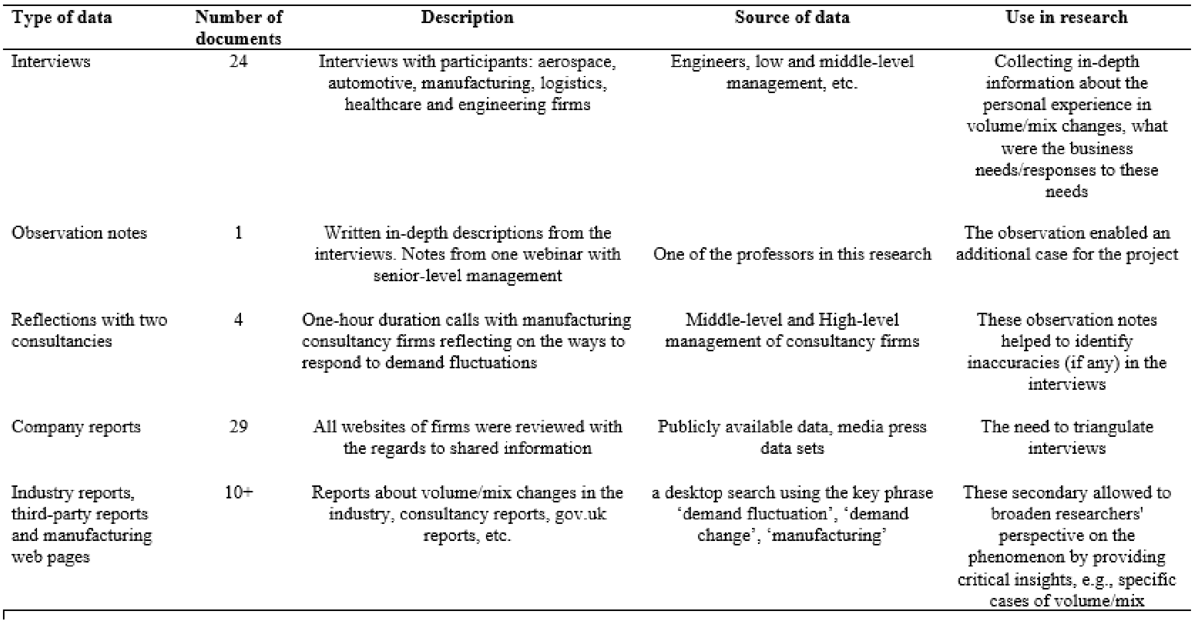
Appendix A. The data collection sheet



Current industrial challenge 1: Communication	**Context of challenge:** *Internal or external or both?* Internal: Delays or extended waiting times when organising productions plans, updating on efficiency and productivity and solving problems External: Covid pandemic	**Current response to challenge:** *How do you intend to cope with this challenge?* Reduced shifts Work from home when possible Technology purchase Looking after the morale of teams Staff contributed a % of their salary to avoid laying off.	**Constraints and barriers you face when tackling this challenge?** Cost of testing Quarantine periods required longer time to travel between plants	**In scope for which projects? New Project?**
Current industrial challenge 2: Supply of steel and metal products	**Context: Int. or Ext. factors?** External: Ukraine conflict *Required to supply parts on time, with quality*	**Current response:** An aggressive program to increase productivity Investing in machinery and equipment Re-negotiate contracts	**Constraints and barriers:** Extra cost of parts Risk of increasing prices	
Current industrial challenge 3: WIP management and storage	**Context: Int. or Ext. factors?** External: Brexit and Ukraine conflict. Supply chain logistics and shipping problems Internal: storage problems	**Current response:** Increasing WIP Scale for the business Now implementing a program to reduce inventory	**Constraints and barriers:** It might reduce flexibility	

Appendix B. The data sources utilised in the research project



Type of data	Number of documents	Description	Source of data	Use in research
Interviews	24	Interviews with participants: aerospace, automotive, manufacturing, logistics, healthcare and engineering firms	Engineers, low and middle-level management, etc.	Collecting in-depth information about the personal experience in volume/mix changes, what were the business needs/responses to these needs
Observation notes	1	Written in-depth descriptions from the interviews. Notes from one webinar with senior-level management	One of the professors in this research	The observation enabled an additional case for the project
Reflections with two consultancies	4	One-hour duration calls with manufacturing consultancy firms reflecting on the ways to respond to demand fluctuations	Middle-level and High-level management of consultancy firms	These observation notes helped to identify inaccuracies (if any) in the interviews
Company reports	29	All websites of firms were reviewed with the regards to shared information	Publicly available data, media press data sets	The need to triangulate interviews
Industry reports, third-party reports and manufacturing web pages	10+	Reports about volume/mix changes in the industry, consultancy reports, gov.uk reports, etc.	a desktop search using the key phrase 'demand fluctuation', 'demand change', 'manufacturing'	These secondary allowed to broaden researchers' perspective on the phenomenon by providing critical insights, e.g., specific cases of volume/mix