Enabling Coordinated Elastic Responses of Manufacturing Systems through Semantic Modelling

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Abstract: Resilience to supply chain disruptions and to changing product volumes and specifications are currently major challenges for the manufacturing sector. To maintain quality and productivity, manufacturers need to be able to respond to disruption using a coordinated set of strategies across different levels of the business, from changes on the shop floor to changes in business strategy. To achieve this coordinated response in the most effective way – what we refer to as an *elastic response* – a first step is to clearly understand what resources, capabilities and business strategies are available, and then identify viable solutions that may include adding or removing equipment, re-purposing assets, adapting shifts, changing suppliers, or outsourcing part of the process. As manufacturing systems move towards more dynamic, flexible environments, a digital representation of the capabilities at all levels of the business as well as real-time status of these will play a key role in achieving a true picture of the state of a system and support the decision-maker to deliver an effective elastic response. This paper presents a semantic approach to the underpinning models needed to enable such response. By semantically representing capabilities at all levels, a semi-automated process can be implemented to reason and match process demands to capabilities. This is the first step in understanding if the existing system can cope with the disruption or if there are any other existing means in the business that can be used to enable an effective response.

Keywords: Semantic modelling, Manufacturing ontology, Reconfigurable systems, Elastic reasoning, resilience

1. INTRODUCTION

A major challenge that manufacturing companies face today is the ability to be responsive to dynamic and changing demands whilst maintaining quality and productivity. Companies look for ways to address these disruptions (e.g. changes in product specification or raw material availability) through a set of business strategies that include adapting their existing processes on the shop floor, increasing storage, outsourcing, or building new plants due to limited capacity. Businesses continuously develop *contingency plans*, which provide temporary solutions and are frequently not optimal, therefore have to be improved through experience (Onica et al., 2022). Such sub-optimal contingency plans lead to inefficient processes that do not meet production goals.

At the shop floor level, one of the factors that limits a manufacturer's response is systems design. Many decisions made during the design process restrict the later implementation and operational capabilities of the system, which effectively limits even the experienced manager's response to disruptive events (Battesini et al., 2021). Flexible and reconfigurable systems are an important step towards resilience from a shopfloor perspective (Gu et al., 2015), however, this does not constitute the only dimension in a companie's options to respond to disruption. At the operational and strategic level of the business, policies and philosophies play an important role as well. Policies turn into rules that may improve or constrain how resources and processes are used (Object Management Group (OMG), 2015). Similarly, philosophies affect business response; for example, Lean philosophies may determine the storage strategies; a key element in responding to supply chain disruptions. Another example is the 'outsourcing' philosophy: whilst for some companies this may provide the main mean for capacity increase, those who follow an 'in-house' philosophy may only consider acquiring new equipment (Fan et al., 2022). Such a decision directly affects the costs that the company bears.

Shopfloor and supply chain reconfiguration have been widely studied separately but very few studies look at the coordination of both as a response (Napoleone et al., 2022). To achieve this coordination effectively, a clear understanding of what the options and limits are at each business level is needed. With a formal definition of what the capacities and capabilities are available, it would then

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be possible to capture and monitor the real state of the system and business. This formalisation and monitoring may reveal hidden capacities that are discovered only when data is better understood. This paper presents a formal definition of these concepts at all levels of the business through the use of semantic models. The information that is captured is then used to support the decision-making steps – referred here as *elastic response* – when responding to a change or disruption. The rest of the paper is organised as follows. Related work on data modeling and semantics for manufacturing, as well as how these are used to support automation is introduced in Section 2. Section 3 briefly introduces the concept of elastic systems and the elastic response process, presents the proposed data models in detail, and shows how the data models are used to support this process. Section 5 demonstrates with an industrial scenario how the semantic models support the response process. Section 6 presents a discussion of this scenario, conclusions, and future work.

2. RELATED WORK

To remain competitive, manufacturing companies are continuously looking for new ways and technologies that will support them in a highly competitive market. In modern manufacturing the focus has been on digital technologies; from computer-aided design, numerically controlled machines, plant and process simulation, and the digital twin. All these have a common fundamental requirement: the need for advanced information technologies that can not only integrate these sources of information but that allow all created data to be structured, life-cycle managed and interpreted in order to bring higher value to the business.

There have been some early efforts on defining common manufacturing models to support the capture and integration of information in a business which is then used to improve decision-making. Resource capability models have been proposed in the past in various works, e.g., Ratchev (1998), Shiau et al. (2000) and Järvenpää et al. (2018b). Ratchev (1998) proposes a system-based approach to manufacturing where resource capabilities can be selected optimally for process planning. Gutiérrez (1995) developed a manufacturing model with four levels: factory, shop, cell and station, where the latter also captures the individual physical equipment. Using an object-oriented approach, taxonomies for processes, strategies and resources are defined, which are necessary to enable adequate manufacturing information flow between different information systems of a business. This manufacturing model is one of the holistic approaches that captures all levels of the business, but lacks the necessary details of the capabilities at the lowest levels as well as details outside the system, e.g., supply chain strategies and services, or the product bill of processes and materials. Zhao et al. (1999) take this work further by introducing a product model and uses the same object-oriented approach to introduce the concept of the virtual enterprise. The authors show how the captured data can be potentially used for matching manufacturing capabilities against product requirements.

More recent work has taken these capability, resource, productand process models, and adapted them into a semantic approach. Semantic models provide the means to standardise how information is shared and interpreted across multiple systems. Lin and Harding (2007) present some of the early works on the definition of manufacturing taxonomies and axioms to enable cross-understanding of manufacturing concepts across different manufacturing systems engineering applications. The authors demonstrate how efficient access to data supports multiple manufacturing activities such as mapping product design to materials inventory. Compared to object-oriented models, semantic models provide reasoning capabilities which simplify and facilitate to some extent the process of concept matching. Usman et al. (2013) present further developments towards reference ontologies for manufacturing. Using existing standard ontologies, the authors extend these to capture manufacturing concepts which are validated in an aerospace use case, showing how the model supports integration of information between design and manufacture.

In the work by Järvenpää et al. (2018b), semantic models provide a way to formally capture manufacturing assets, capabilities, as well as product specification and processes associated with its manufacture. Using these models and reasoning rules and queries, the authors perform capability matching which automatically suggests combinations of assets that can deliver each process or required operation. A similar work has been done by Weser et al. (2020), demonstrating with a basic capability model C4I, asset and task model, how capabilities in asset instances can be checked to simplify and support the manual process.

Most of these are production-oriented models, but a critical aspect in manufacturing is the supply chain. Ye et al. (2008) describe semantic ways of capturing the main concepts related to supply chain, including their structure, corresponding parties and roles they all play: from vendor, through supplier, to customer. In contrast to the work by Fadel et al. (1994), where the supply chain is only implicit and relates to internal enterprise processes, Ye et al. (2008) links the enterprise to the network-wide, both internal and external, chain of processes, responsibilities and roles, all of which are crucial in enabling a coordinated and fast response to changes in the market. Some attempts to combine the various aspects of the manufacturing enterprise have been developed in the TOVE (Fox et al., 2002) and FLEXINET (Palmer et al., 2018) projects. Despite similar aims, the work presented here focuses more on developing an ontology that supports the elastic reasoning process, described in the next section.

3. ELASTIC MANUFACTURING SYSTEMS AND ELASTIC REASONING

In many sectors and regions manufacturing is moving away from classical manufacturing lines to approaches such as Flexible Manufacturing (Jain et al., 2013) and Reconfigurable Manufacturing Systems (Koren et al., 1999) as a way to respond to disruptions, particularly dealing with changes in demand and high customisation. However, these approaches are focused mainly on the physical flexibility. As recent global disruptions such as the COVID pandemic have shown, a more coordinated response is needed, whereby manufacturing capabilities and services at different levels of the organisation can be provisioned and de-provisioned to meet the current demand as closely

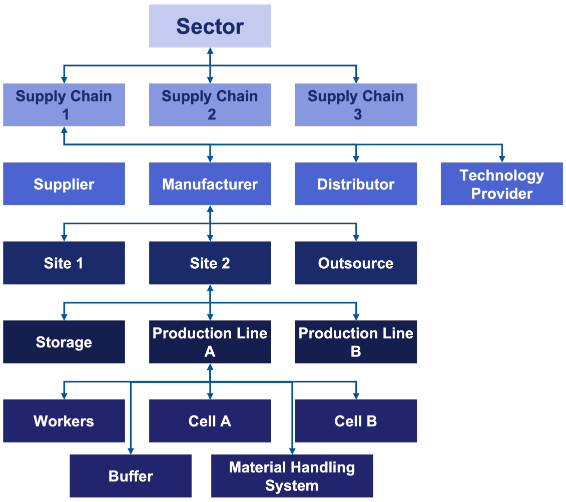

Fig. 1. A system's elasticity may be achieved vertically across the value chain or horizontally, rebalancing and reassigning across subsystems.

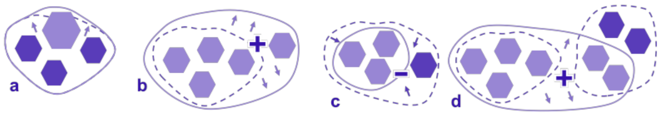

Fig. 2. Four elastic transformations, including: a) utilising built-in elasticity, b) adding assets, c) removing assets to be utilised elsewhere, d) extending the facility into the supply chain.

as possible and cost-effectively. Having the ability to respond to disruption in such manner is what we define here as *manufacturing elasticity*. We define an *Elastic Manufacturing System* as a system that is not constrained by the physical capabilities on the shop floor but one that can easily provision and de-provision capabilities using both internal and external resources, ensuring that at all times the commissioned system has minimal cost; that being energy costs, unit costs, reconfiguration costs, or any other constraint that drives the business. Different manufacturing systems may have different levels of elasticity and such elasticity can be achieved through different means, what we refer here to as *elastic dimensions*:

- Control Elasticity - a system's ability to change its control strategy in response to changing requirements;
- Capability Elasticity - the ability to extend the set of processes capabilities in response to changing product requirements and process provision;
- Production Elasticity - the ability to deploy local and third party resources in the most productive way.

An elastic system is able to match capacity and capability to demand through the optimisation of system configuration and business strategies and adopting manufacturing as a service models, to ensure spare capacity and capability is utilised. The system may increase its ability to respond by either working vertically on the value chain (see Fig. 1) or by balancing and reassigning capacity across sub-systems within the same level of the chain.

When responding to a disruption, an elastic system goes through an *elastic transformation*, which is the change that is adopted to meet such demand. Four possible transformations enabled by the elastic dimensions are proposed (Fig. 2). A system may respond to a demand by either (a) using existing resources but to a higher (or lower) utilisation rate, (b) adding additional resources or services to the current system, (c) removing resources or services and (d) adding external resources or services by third party suppliers. How the transformation is decided will depend on the current system and the business goals. This decision-making process is what is described here as the *elastic reasoning* process. This process is triggered as a demand or disruption reaches the business (see Fig. 3) and the main steps of this process are the following:

(1) *Analyse facility.* Understand what is currently available in terms of capability, capacity and utilisation, to determine if the current disruption can be handled by the existing commissioned system, and requires only a change in the level of utilisation. This is then used in step (3) to adequately balance the load.
(2) *Formulate solutions.* If a simple increase (or decrease) in utilisation of the existing system is not the answer, then other options are explored. These could be: looking at alternative equipment available, outsourcing, or increasing capability by acquiring new equipment.
(3) *Optimise selections.* From the potential solutions gathered, the best option is selected according to an optimisation criteria that might be different for each business and that might require a trade-off between multiple goals. The system could be optimised for minimum change, minimum cost, or for enhancing future responsiveness. If, after optimisation, a set of potential solutions are available, then the human expert makes the final informed decision.
(4) *Implement response.* The selected response is implemented and the state of the new system needs to be updated for future elastic reasoning processes.

In order to perform each of these steps, it is critical that all information is available at all times to be a true representation of the current state of the business. In this paper we propose the elastic reasoning process to be semi-automated, and so a semantic representation of capabilities at all the levels (Fig. 1) is a key element. The model enables the connection of information about available resources, constraints and business rules and the reasoning steps that support the final decision making.

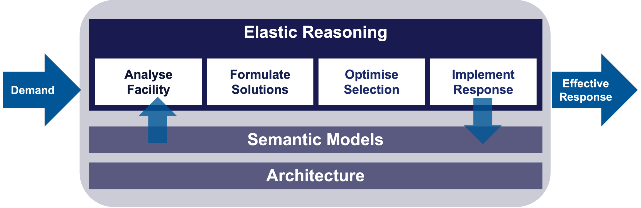

Fig. 3. The Elastic Reasoning process is supported by the underlying semantic models to ensure digital representations remain as accurate as possible to the current actual state of the system and business.

4. SEMANTIC MODELS FOR THE ELASTIC RESPONSE

Developing further from the models proposed by Järvenpää et al. (2018a), Gutiérrez (1995) and Ye et al. (2008), this work proposes the modelling of assets, capabilities, and the business rules that constrain such resources to support capability matching and optimisation of the system to respond to changes in demand. This is achieved through the following six semantic models:

- *Product model* captures the demand or disruption, which may be an increase or decrease in volume or change in product type and is linked to a product. Product information is captured in relation to the bill of materials and processes and how product parts link to processes.
- *Resource model* defines how assets can be used in terms of materials, precision, speed, mobility and other characteristics. Assets refer to hardware (machines, robots, material handling equipment, storage), human resources, or a combination of these. Capacity elasticity is characterised through the capture of shifts, utilisation and location of assets. Control elasticity is captured by defining the programmability of assets and human skills.
- *Capability model* defines what assets can do. Capabilities are defined as single or combined, depending on how assets are used individually or as a combination (e.g. a robot and an end effector have a combined capability ‘pick and place’).
- *Capacity utilisation model* describes the Key Performance Indicators (KPIs) and how these can be aggregated to measure assets and supply chain utilisation (Elshafei et al., 2023), and used to optimise utilisation at all levels.
- *Business strategy model* describes concepts related to the business strategic decisions and operational rules. The model dwells on the business policies and rules, and entails strategies of the production facility, technology used, storage, as well as relations with the external suppliers and service providers.
- *Process model* defines the common language between the bill of processes and asset capabilities which enable capability matching.

Fig. 4 presents how the models are linked to perform a matchmaking process. Fig. 5 presents the overview of the main concepts captured by the above models as well as relationships between them. More lower level concepts are omitted here due to lack of space.

To enable each of the steps of the elastic response, a semi-automated solution was developed. Ontologies were implemented in Protégé and, through SPARQL queries, a product bill of processes is matched against assets and suppliers capabilities. Volumes demanded are then assessed based on the utilisation metrics that are obtained through the capacity model but also considering the business policies that affect those assets. Once a set of options are drawn, optimisation is done depending on the specific business constraints. The implementation details of these two processes are omitted in this paper to pay more attention on the value of ontological elements to the decision process.

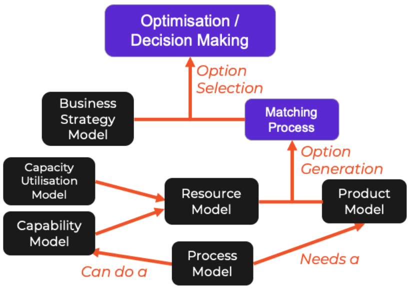

Fig. 4. Linking semantic models in the optimisation and decision-making process for the elastic response.

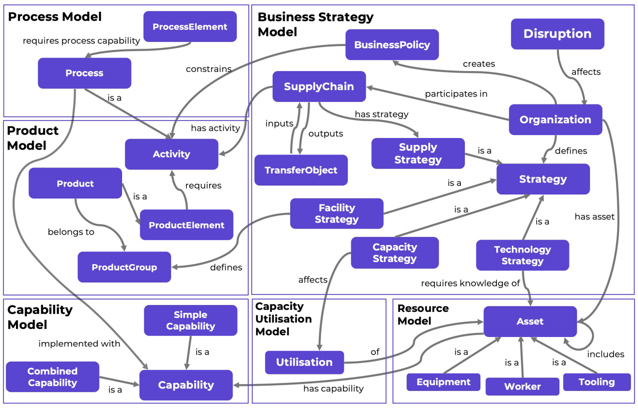

Fig. 5. The main concepts and relations between the presented semantic models.

5. INDUSTRIAL USE CASE: HINGE ASSEMBLY

This section presents an industrial use case based on the assembly of an automotive interior hinge product. Given some disruptions to the business, the elastic reasoning process and the supporting ontology concepts are presented in detail. Concepts linked to the elastic ontology are presented starting with capital letter whilst instances are in `typewriter` font.

5.1 The hinge assembly process

Let us consider a manufacturing firm which among their Products offers a hinge product. To Manufacture the hinge product, a Production Line with several Cells is commissioned. The line consists of Assets (robots) for Assembling the hinge, a Material Handling System, and Workers to load the hinge components and unload the hinge after assembly. A hinge consists of the following Parts: single leaf, double leaf, retainer, detent tube, springs and balls. The `HingeAssembly` process consists of the Assembly Steps presented in Figure 6, which occur one after another. Each of these steps require specific capabilities such as PickAndPlace, PneumaticPick and Insert. Additionally, after assembly, a VisionTest of Retainer and ForceTest of Detents is performed. Inside a cell there are two robots with capabilities PickAndPlace, VaccumPickAndPlace and ApplyForce, and a hinge testing station, capable of performing VisionTest and ForceTest. The robots can perform the whole Assembly procedure on their own, but share EndEffectors and Tools, which lay in a shared ToolRack. A Cell can be extended with additional robots.

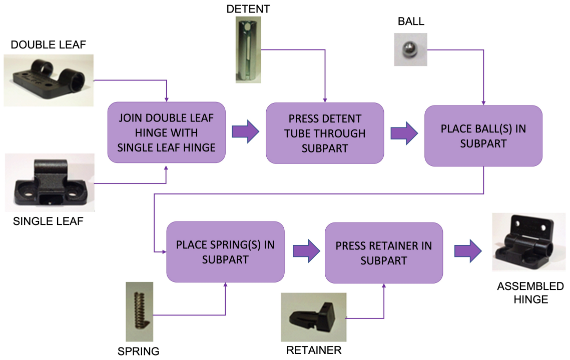

Fig. 6. Assembly steps which are automated using robotic assembly.

There are two variants of a Hinge product, `Hinge1`, which has 2 balls and 2 springs and `Hinge2` which has 3 balls and 3 springs. `Hinge1` is manufactured on `ProductionLine1` and `Hinge2` on `ProductionLine2`. The demand for `Hinge2` is expected to increase by 50% for the short-term. Both the increase and future decrease are classified as a Disruption, and as such short-term solutions are searched for. In order to meet the demands, several Scenarios can be considered, which are described in the following subsections.

5.2 Responses to demand increase

Following the elastic reasoning process and the possible transformations (Fig. 2), the first step is to understand what assets, capabilities and options are available and from there generate a set of possible response Scenarios. Although it would depend on the business *elastic philosophy*, it is assumed that a business may want to first address the problem by understanding if it can be done with existing resources before considering any longer-term change (i.e. elastic transformation (a)). Drawing from a capability matching performed in step 1 of the reasoning process, the following responses become available:

- The current setup can be utilised by working Overtime. Making this decision bears some costs, especially paying overtime wages to the manual workers, and increased costs of energy for higher utilisation of the electrical equipment. In this case, the *Capacity utilisation model* is used for showing how much can the existing capacity be increased.
- Since `Hinge1` is MadeToStock, its production can be temporarily reduced or even stopped due to current stored product available to meet the demand of Hinge1, and `ProductionLine1` can be used to manufacture `Hinge2`. This requires the reconfiguration of robots on `ProductionLine1` which also bears a cost.

These alternatives are input into the optimisation process (step 3 in elastic reasoning) and a final choice is made by the decision maker. By formally capturing capabilities across the lines, it is possible to automatically draw these scenarios and check their feasibility instead of relying on the expertise of operators and having to perform the actual change before it can be verified that the need is met.

If the demand cannot be met by utilising the current capacity, elastic transformations (b) and (d) are explored during optimisation drawing again from the possible configurations captured in the semantic models as follows:

- A decision can be made to purchase a new robot and install it in `ProductionLine2`, where `Hinge2` is manufactured (transformation (b)). This bears the costs of purchasing new equipment and increased energy costs. Moreover, if the BusinessPolicy dictates that all the hinges need to go through inspection, then this can lead to working overtime as more hinges need to be inspected, or to acquiring a new inspection system. To leverage this, a statistical approach to testing can be implemented, which however means the business policy would need to be changed.
- The BusinessPolicy dictates that at least 20% of the current production is subcontracted to other companies, which play a role of Manufacturer in the firm's supply chain. The Subcontracting capacity can be increased to, say, 50% or additional Subcontractor can be found with a short-term contract (case (d)).

All of the above scenarios are drawn from the captured semantic data and have their advantages and disadvantages which need to be balanced when making the final decision. All options will bear some cost and the optimisation criteria may either require a minimisation of the cost, or possibly a maximisation of elasticity for a more flexible response in the future. Including as much as possible details into the semantic models allows to make the decisions in the most optimal and automatised way. In addition to the production-related problems, further decisions need to be made regarding RawMaterial availability and the SupplyChain. If the company stores some amount of the raw material, the Reserves can be used to produce `Hinge2`. In case the amount of reserves is not enough to cover the demand for producing `Hinge2`, the company needs to IncreaseSupply from the existing Suppliers or find an additional Supplier for that RawMaterial. If the Supplier cannot meet the demand, this is classified as a Disruption and the elastic reasoning process is triggered once again.

5.3 Responses to demand decrease

In this subsection, the possible responses to demand decrease are shown, which may follow after the short-term increase depicted in the previous subsection. The alternative scenarios will once again be linked to the corresponding elastic transformations. The responses corresponding to the transformation (a) from Fig. 2 are the following:

- Working Overtime can be reduced to normal working times, reducing the utilisation of the current capacity.
- After the demand for `Hinge2` is met, another repurposing and reconfiguration occurs, which allows to bring the production of `Hinge2` back to only `ProductionLine2`, while the manufacturing of `Hinge1` is carried out on `ProductionLine1`.

Transformations (b) and (d) can be followed by removing an asset, which corresponds to transformation (c), or transformation (a). The latter assumes that the purchased equipment or new subcontractors have been classified as firm's assets. The corresponding set of choices is as follows:

- If new robots were purchased, the utilisation of these could be decreased and made available to other pro-

duction lines or future response (case (c)), or both old and new robots can be repurposed for manufacturing `Hinge2` and `Hinge1` in original volumes. A decision can be made to adopt the original testing inspection or to keep the new approach.
- Subcontracting is reduced back to the original amount. If a new subcontractor was found, the short-term contract will likely cease (case (c)). Alternatively, the compay may preserve the links with them, the contract is extended but the amount of hinges produced by the new subcontractor is reduced (case (a)).

The hinge example shows how the semantic concepts that are captured can support not only automated matching of physical assets, but consider other capabilities available to the business that, depending on the business goals, may be better options for responding to a disruption.

6. CONCLUSIONS

This paper proposes an semantic modeling approach that enables a holistic capture of manufacturing capabilities across different levels of business as a first step to achieve coordinated responses to disruption. Such a response, called the *elastic response* consists of performing a matchmaking between the requirements and available assets and capabilities both in terms of physical resources as well as the elements of the supply chain, business rules, and policies. This is implemented by linking several semantic models. The presented disruption scenario shows some key elements of the semantic model that are necessary throughout the reasoning process. As the semantic model captures not only physical resources but all options available to the business throughout the value chain and their feasibility through the business strategies and constraints, it is possible to develop a more holistic understanding of the impact of each disruption and assess the impact of alternative scenarios, which results in creating a more informed response to such disruption. The whole reasoning process is complex, and the scenario presented here is a simple approximation of the usage of a semantic model. A larger automation of the decision process is currently under development.

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