Investigating Multi-level Ontology to Support Manufacturing during Demand Fluctuation

Nikolai Kazantsev[1], Karol Niewiadomski [2*], Giovanna Martínez-Arellano[2], Basem Elshafei[2], Fan Mo[2], Sudhir Rama Murthy[1].

[1] Institute for Manufacturing (IfM), University of Cambridge, 17 Charles Babbage Rd, Cambridge, UK
[2] Institute for Advanced Manufacturing, University of Nottingham, 522 Derby Rd, Lenton, Nottingham, UK
[*]karol.niewiadomski@nottingham.ac.uk

Abstract: Responding to demand fluctuations represents a challenge for manufacturers, as they often face resource limitations and cannot assess all potential solutions. This paper presents a low-cost semantic engineering solution (ontology) to coordinate potential responses to disruption at the supply chain, factory and firm levels. The research method uses three cycles of design science research to develop a multi-level ontology and assess its potential to coordinate responses. The feedback from companies positions ontology as a solution for stress-testing next generation manufacturing systems. Using semantic engineering, companies can assess the available responses before disruptions, plan potential responses, and support their decision-making during demand fluctuation.

1. Introduction

'Black swan' events - such as military conflicts, pandemics, and semiconductor crises - drastically change product volume and mix patterns and shorten how manufacturers can respond. This is a particular challenge for highly regulated industries, such as aerospace, automotive, and food manufacturing, where regulations reduce agility. A great help for manufacturing companies would be the ability to visualise and test the potential disruptions. For example, by available responses to demand shock or component scarcity can raise preparedness for the future disruptions.

This paper develops a low-cost open-source solution (multi-level ontology) to create a knowledge base for a manufacturing system at changes at firm, factory and supply chain levels. Such a multi-level ontology utilises the wealth of existing ontologies to represent a potential disruption, such as demand shock or component scarcity. Presented are the main concepts and relationships that capture the information flow on the three levels of a manufacturing system. They make it possible to infer new relationships among the data semantic rules and discover possible solutions to the disruption. The proposed low-cost open-source solution can be used as a stress-testing tool to simulate product volume/mix change and construct the optional responses across the levels (see Fig. 1).

Due to the open-source ontology development, this solution is accessible to all firms, regardless of size and market power. We apply the tool to the EPSRC-funded Elastic Manufacturing Systems (EMS) project context. The approach builds upon methods recently used in elastic computing resource allocation and draws on the principles of collective decision-making, cognitive systems intelligence and networks of context-aware equipment and instrumentation. We hope the tool will inform the design of future manufacturing systems operating under demand shocks and fluctuations common in the VUCA world.

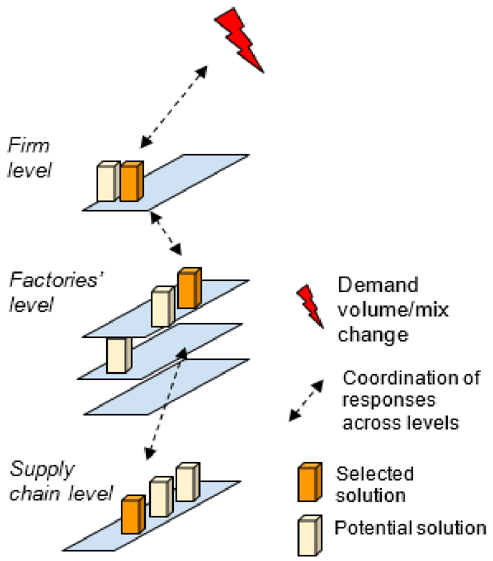

Fig. 1. *Conceptual model of responding to product volume/mix change across all the levels*

2. Thematic background

An ontology is 'an explicit specification of a shared conceptualisation' [1] that can inform with automated reasoning the coordination of interactions between the layers of a manufacturing system. Regardless of a firm size or market power, applying knowledge representation mechanisms will help to manage complexity and drive productivity gains. The early works' potential of ontological relationships and axioms to support reasoning has been a subject of renewed interest in Industry 4.0 research for an automated team, product, and process composition [2-5], resource management for aerospace manufacturing [6], aircraft manufacturing system design [7], Reconfigurable Manufacturing System design [8], and supporting demand-driven collaborations in low volume high variability manufacturing [9].

https://doi.org/10.1049/icp.2023.1752
This is an open access article published by the IET under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0/)

Demand shocks often cause supply chain disruptions due to insufficient raw material, labour and financial resources [10]. The lack of effective information-sharing mechanisms represents another problem, as it cannot coordinate responses between the supply chain participants [11]. Arguably, better connectivity across participants would help avoid vulnerabilities of interconnected supply chains, hoarding behaviour and mismatches between inventory and capacity. Coordinating responses across the different levels of the supply chain can be a way to achieve better resilience against disruptions.

Here is where ontologies may play a vital role. Our Research Question (RQ) is: 'What is the *multi-level ontology that can be used to coordinate manufacturing responses*?'

3. Method

We selected the design science methodology to address the proposed research question [12, 13] (See Fig. 2). We build a purposeful artefact – The Multi-level ontology - to address a business problem – the need to react to demand volume/mix changes and supply chain disruptions at several levels. Some results of individual design activities have already been documented in earlier publications [14].

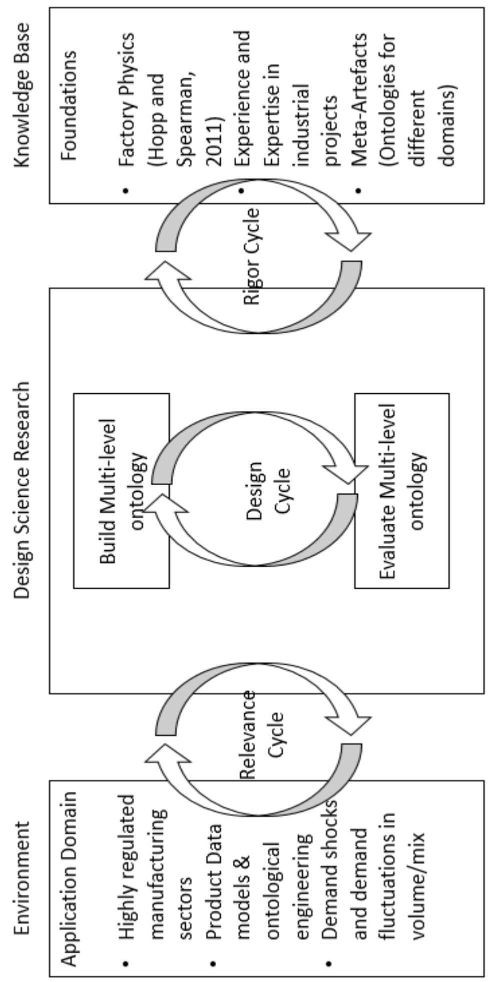

Fig. 2. *DSR process (adapted from [13])*

Our work on the EPSRC-funded Elastic Manufacturing Systems (EMS) project enabled conditions for data collection through a cyclic checking of the relevance of the concepts in the ontology with industry. The purpose of the Relevance cycle was to collect requirements for the multi-level ontology based on the purposeful interactions with practitioners. We used thematic analysis [15] to derive requirements for the multi-level ontology.

The Design cycle enabled the iterative development of a multi-level ontology using some details from top-level and production systems ontologies, for example, enterprise ontology [16], the concepts of strategies across the manufacturing facility [17], concepts of capabilities and processes from [5], and concepts related to parties and supply chains [18]. [19] leveraged the ideas of competency questions and test-before software development. [20] a methodology for ontology building derived from the Unified Software Development Process. The evaluation using the automotive case study followed a technical risk and efficacy strategy [21], where a design artefact's utility, quality, and usability have been selected as crucial acceptance criteria for the ultimate evaluation of the research results. Inconsistencies with requirements triggered more iterations of the relevance cycle that started with environmental feedback

Finally, in the Rigor cycle, we contribute to low-cost industrial engineering by providing an easy-to-use semantic tool to stress test manufacturing responses to demand change at three levels and to coordinate the response. As the solution is open source, any manufacturing firms (inc. SMEs) can use it and coordinate responses to disruptions without external facilitation [22].

4. Findings

The Multi-level Ontology was created to enable integration between three levels of the value chain: (1) Firm level, (2) Factories level; (3) Supply chain level. For the shop floor level, we integrate *Resource, Process* and *Capability* ontologies [4], which link the physical and human resources of a manufacturing firm with the capabilities of these resources. Our Ontology imports these models and slightly reorganises the concepts to capture various aspects of supply chain and business levels. It also proposes new concepts related to business strategies, supply chains and key performance indicators. The processes captured in the process model are linked with the capabilities required for their implementation by the relationship: *requires process capability*. The main concepts are described in the paragraphs below. In the remainder of this chapter, the concepts captured in the ontology are written with capital letters and italics, the object and data properties starting with small letters and in italics, while the individuals are denoted using the `Courier` font.

Disruption is an interruption of a normal process and is related to the *Process* class via the relation *interrupts*. However, because different disruptions can be explicitly linked to a supplier or product, this relation is inferred rather than assigned in the Elastic ontology. Disruption is classified into three categories: *Demand shock, Internal Disruption*, and *Supply chain disruption*. The first has two subclasses: *Demand increase* and *Demand decrease* for a particular product. Internal Disruption relates to Disruption due to processes such as strike action or a machine break, which occur within the firm boundaries, particularly on a production systems level. Finally, *Supply chain disruption* is classified into four categories: *Extended lead time, Loss of supplier,* *Price inflation*, and *Reduced volume*. The first two relate to a particular supplier, while the last two are related to a particular *Product* or *Raw material* needed to manufacture a product.

A Strategy class represents the possible options that a company might pursue. The strategy is divided into classes relating to various company levels: *Capacity strategy, Technology strategy, Facility strategy* and *Supply chain strategy*. The technology and facility strategies relate to the production systems; therefore, their further description will be omitted here. The Capacity strategy in the context of Elastic Manufacturing Systems relates to possible strategies for increasing capacity. The class is divided into: *Increase Shifts, Use inventory buffer, Overtime, Reconfiguration*, and *Subcontract*.

The *Capability* class is divided into *Simple* and *Combined* capabilities. In the original Capability model, a Simple capability is one possessed by a single device, while a Combined capability is that of a combination of devices. For example, a class *Robot* is only capable of Moving and an instance of *Gripper* is capable of Grasping and Releasing. If these two devices are connected, they form an instance of a Device Combination and possess combined capabilities, particularly *Picking*, *Placing*, and *Transporting* capabilities.

The classes for these combined capabilities are defined within the capability model and their relations with simple capabilities are explicitly asserted by the relation *hasInputCapability*. Following the approach of combining the capabilities, in the Elastic ontology, the Combined capability class has been further subdivided into two subclasses: *Shop floor capability* and *Business capability*. This distinction has been made to explicitly differentiate between the capabilities of machines, devices or human resources as realised in shop floor processes, from the capabilities of enterprises. The former, *Shop floor capability*, is equivalent to a *Combined capability* from the capability model, while the *Business capability* can consist of *Simple* and other *Combined capabilities*, particularly shop floor capabilities. In application-specific ontologies, it is beneficial that the combined business capabilities are as general as possible, enabling the discovery of businesses with non-standard capabilities. For example, one can think of a manufacturing firm that requires customised plastic cases for packaging their product. In case a packaging supplier cannot satisfy the demand, the manufacturing company could find a firm with *Additive Manufacturing* or *3D Printing* among their capabilities and use these capabilities to produce specialised casings. Another example of a non-standard capability is that of Alcohol distilling. A company with this capability and producing alcoholic drinks can also be discovered as a potential producer of hand sanitiser.

The Process class has been divided into two more subclasses: *Planned process* and *Consequential process*. A planned process is further divided into a *Business* and *Monitoring* processes. A business process is one related to the operations of an enterprise. It includes concepts such as *Sourcing* (-raw material), *Transporting, Delivering, Purchasing,* and *Manufacturing Processes*. These processes enable the sourcing, exchange and manufacturing of product elements. The manufacturing process is subclassed into Setup, i.e. the preparation before the actual manufacturing stage, *Value add process*, i.e. one which adds value to the product, and *Supporting process*, i.e. one which doesn't directly add value to the product but is needed to perform a manufacturing operation; this separation makes Process class [4] equivalent to *Value-add process*. Planned processes can have accompanying consequential processes. In the ontology, the link is given by the relationship *hasConsequentialProcess*. A consequential process is one which occurs in parallel to a planned process and results in some byproduct. For example, any manufacturing process using electrical devices has a consequential *Energy consumption*. Moreover, some processes have inevitable *Greenhouse emissions*.

A class *Monitoring process* is a subclass of 'monitors some Process'. This class is also linked to a *Key performance indicator*, which measures the performance of operations and the unplanned processes' by products, i.e. the energy consumption in kWh or carbon emissions in GTCO2.

5. Conceptualisation

This work develops a low-cost semantic solution for stress-testing manufacturing enterprises with an uncontrollable environment, focusing on demand shocks and fluctuations. Such an open access ontology allows to capture and model potential disruptions, such as demand shock or component scarcity, and suggest optional responses across the levels for a manufacturer regardless of their size or market power. The authors have used open-source tools for creating ontology which will make the solution usable by multiple industries. Such a solution can help provide a unified, interoperable platform to discover and infer the solutions to the disruptions in supply chain and demand fluctuations.

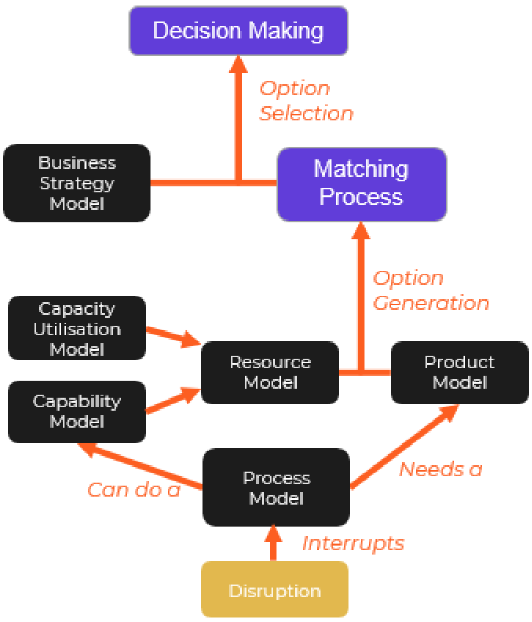

Fig. 3. *Conceptual model of responding to product volume/mix change across all the levels*

To guide resource allocation across the factory, firm and supply chain levels, our approach represents a valid opportunity for the next generation of manufacturing systems.

6. Conclusion

This paper developed an open-access low-cost semantic engineering tool (multi-level ontology) to inform the design of future manufacturing systems. These systems will be able to operate under demand fluctuations. We propose that combining these responses across factory, firm and supply chain levels produces the best result in responding to volume/mix change and will advise on provisioning and de-provisioning resources and scale outputs cost-effectively. Hence, elasticity emerges from coordinated transformations at all levels of the value chain.

The limitations of multi-level ontology include the lack of guidance on increasing the adoption of semantic engineering within the manufacturing sector. In particular, adopting such tools within SMEs might be a strong barrier. It will be interesting to see how this ontology will vary with different industries or with respect to the notion of VUCA. Future research will focus on model validation or extension in other industries. In this regard, comparing results with less regulated industry sectors could extend the application of the low-cost tool. Future work needs to consider developing a friendly user interface to enable better adoption of the low-cost semantic engineering solution.

7. Acknowledgments

The first author acknowledges the funding role that helped support this research: the ESRC Made Smarter Network+ ('InterAct') Commissioned Research Programme, Early Career Researcher Fellowship number J17293/ES/W007231/1. EPSRC-funded Elastic Manufacturing Systems (EMS) is a consortium of three universities: Nottingham (Advanced Institute for Manufacturing), Cambridge (Institute for Manufacturing) and Imperial College London, with 11 industrial organisations from the UK (grant agreement no. EP/T024429/1).

8. References

[1] Gruber, T.R.: 'Toward principles for the design of ontologies used for knowledge sharing?' International journal of human-computer studies, 1995, 43, (5-6): pp. 907-928

[2] Cisneros-Cabrera, S., et al.: 'An approach and decision support tool for forming Industry 4.0 supply chain collaborations', Computers in Industry, 2021, 125: pp. 1-16

[3] Liu, Z., et al.: 'The architectural design and implementation of a digital platform for Industry 4.0 SME collaboration', Computers in Industry, 2022, 138, 103623

[4] Järvenpää, E., et al.: 'Semantic rules for capability matchmaking in the context of manufacturing system design and reconfiguration', International Journal of Computer Integrated Manufacturing, 2023, 36(1): pp. 128-154

[5] Järvenpää, E., et al.: 'The development of an ontology for describing the capabilities of manufacturing resources', Journal of Intelligent Manufacturing, 2019, 30(2), pp. 959-978

[6] Arista, R., et al.: 'Industrial Resources in the design of Reconfigurable Manufacturing Systems for aerospace: A systematic literature review', Computers in Industry, 2022. 142

[7] Arista, R., et al.,:'An Ontology-based Engineering system to support aircraft manufacturing system design', Journal of Manufacturing Systems, 2023, 68, pp. 270-288

[8] Arista, R., et al.: 'An Ontology-based Engineering methodology applied to aerospace Reconfigurable Manufacturing Systems design', International Journal of Production Research, 2023, 68, pp. 1-19

[9] Kazantsev, N., et al.: 'An ontology-guided approach to process formation and coordination of demand-driven collaborations', International Journal of Production Research, 2023

[10] Olaogbebikan, J.E. and R. Oloruntoba: 'Similarities between disaster supply chains and commercial supply chains: a SCM process view', Annals of Operations Research, 2019. 283, 1, pp. 517-542

[11] Ergun, O., W.J. Hopp, and P. Keskinocak: 'A structured overview of insights and opportunities for enhancing supply chain resilience', IISE Transactions, 2023, 55, 1, pp. 57-74

[12] March, S.T. and G.F. Smith: 'Design and natural science research on information technology', Decision support systems, 1995, 15, 4, pp. 251-266

[13] Hevner, A.R.: 'A three cycle view of design science research', Scandinavian journal of information systems, 2007, 19, 2. p. 4.

[14] Martínez-Arellano, G., et al.: 'Enabling Coordinated Elastic Responses of Manufacturing Systems through Semantic Modelling', IFAC2023, 2023, Yokohama, Japan.

[15] King, N. and C. Horrocks: 'An introduction to interview data analysis', Interviews in qualitative research, 2010

[16] Uschold, M., et al.: 'The enterprise ontology. The knowledge engineering review', 1998, 13, 1, pp. 31-89

[17] Molina Gutierrez, A.: 'A manufacturing model to support datadriven applications for design and manufacture'. PhD Thesis, Loughborough University, UK, 1995.

[18] Ye, Y., et al.: 'An ontology-based architecture for implementing semantic integration of supply chain management. International Journal of Computer Integrated Manufacturing, 2008, 21,1, pp. 1-18.

[19] Ren, Y., et al.: 'Towards Competency Question-Driven Ontology Authoring. in The Semantic Web: Trends and Challenges. 2014. Cham: Springer International Publishing.

[20] De Nicola, A., M. Missikoff, and R. Navigli: 'A Proposal for a Unified Process for Ontology Building: UPON', in 'Database and Expert Systems Applications, 2005, Berlin, Heidelberg: Springer Berlin Heidelberg.

[21] Venable, J., J. Pries-Heje, and R. Baskerville: 'FEDS: a framework for evaluation in design science research', European journal of information systems, 2016, 25, 1, pp. 77-89

[22] Briggs, R.O., et al.: 'Facilitator-in-a-box: process support applications to help practitioners realize the potential of collaboration technology', Journal of Management Information Systems, 2013, 29,4, pp. 159-194