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IFAC PapersOnLine 59-24 (2025) 102–107

Ontology and Responsiveness in Manufacturing: a Systematic Literature Review of applications

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Abstract: This paper investigates the role of ontologies in fostering responsiveness of manufacturing systems within dynamic environments. As the manufacturing context undergoes a transformative shift from mass production to mass customization, the need for flexibility and adaptability becomes crucial. Focused on different applications derived from a systematic literature review, the study categorizes these cases based on the application of ontologies in manufacturing and their supported functions to critical manufacturing aspects. The findings further underscore how ontologies collectively enhance responsiveness in manufacturing by facilitating adaptation to dynamic environments, fostering efficient communication, and supporting rapid configuration and reconfiguration of production systems. As manufacturing advances toward intelligent and adaptable systems, ontological integration becomes a critical element, enabling interconnected machine networks to quickly navigate changes.

Keywords: Responsiveness, Manufacturing, Ontology, Adaptability, Flexibility, Reconfigurability

1. INTRODUCTION

Today's manufacturing landscape is characterized by a growing demand for diverse, high-quality and customized products, prompting a shift from mass production to mass customization (Khanna and Kumar, 2019). This change introduces challenges, such as the complexity caused by higher product variety and by unpredictable changes or disturbances in the internal/external environment of manufacturing companies (Shoaib-ul-Hasan *et al.*, 2018). As a result, manufacturing systems need to be not just highly flexible, but also responsive in quickly adapting to this dynamic environment (Khanna and Kumar, 2019). Responsiveness, in this context, refers to a system's ability to deal with uncertainty in market conditions while maintaining its production goals (Setchi & Lagos, 2004). Enhancing manufacturing responsiveness relies on factors such as optimal modelling, data interoperability, inter-machine understanding and real-time adaptation (Meng, Wu and Gray, 2020). To address the challenges posed by the heterogeneity of products and product variants, ontologies have been introduced as formal mechanisms to support the integration of business and technical processes (Cheng et al., 2016), and to provide a shared, machine-understandable vocabulary for information exchange among dispersed agents (Ameri, Urbanovsky and Mcarthur, 2012). Defined as formal, explicit specifications of shared conceptualizations, ontologies represent abstract models of real-world phenomena through relevant and well-defined concepts and rules. Their machine-readability ensures precision in their representation, while their "shared" nature indicates that it is collaboratively agreed upon by a group (Cheng, et al., 2016). The ongoing digital transformation complements this by offering technologies to make manufacturing systems more intelligent and adaptable, through cognitive control units (Salis et al., 2023). Future manufacturing systems are envisioned to incorporate these control units, and ontological models contribute significantly to their formal representation (Ameri, Urbanovsky and Mcarthur, 2012). By modelling domain-related knowledge, the ontology can effectively provide domain concept hierarchy, semantic structure, and semantic information sharing, strongly supporting system integration and interoperation (Wan *et al.*, 2018). This work aims to conduct one of the first systematic literature reviews investigating the role of ontologies in supporting responsiveness within manufacturing systems, with a specific focus on their applications, the supported functions and the distinct contributions they provide to enhancing responsive capabilities in dynamic production environments. This paper is organized as follows. Section 2 defines the objective of this study. Subsequently, Section 3 outlines the methodology employed for the literature review. Section 4, instead, introduces a categorization based on the application of ontologies, their supported functions, and their distinct contributions to responsiveness, that is later applied to the examined cases (Section 5).

2. OBJECTIVES OF THIS STUDY

This study aims to systematically investigate and analyze the role of ontologies in enhancing responsiveness within manufacturing systems. As one of the first structured efforts to explicitly connect the concepts of responsiveness and ontologies in the manufacturing domain, this work seeks to provide both a comprehensive overview of existing knowledge and a structured framework to guide future research.

Through a systematic literature review, the study intends to identify and classify contributions based on the application of ontologies in manufacturing and the functions they support. It also aims to derive meaningful insights into how these ontologies help address the challenges of today's dynamic and complex manufacturing landscape.

10.1016/j.ifacol.2025.11.848

As a result, the objective of this work is to develop a conceptual model for classifying and comparing ontology-driven solutions, with the aim of providing insights into how ontologies can be effectively leveraged to improve responsiveness in modern production contexts.

3. METHODOLOGY

This study is based on the application of a systematic literature review to study the relationships between the concept of responsiveness and the ontologies' applications in the manufacturing context.

The first phase was conducted on Scopus® database and consisted in searching the string "responsiveness AND manufacturing AND ontolog*" within titles, abstracts, and keywords. This search yielded a total of 15 articles. Subsequently, each abstract was scrutinized to determine whether it explicitly mentions the development or the reuse of the ontologies to enhance responsiveness of manufacturing systems. As a result, only eleven articles were evaluated as pertinent literature sources as they presented the application of ontologies in the manufacturing domain and, indeed, became the focal point of our investigation.

Reading the full text of these documents resulted in the exclusion of two additional papers, due to the lack of necessary information pertaining to how the application of ontologies in manufacturing processes contributes to responsiveness. This information was, however, present in the remaining papers and was discerned and effectively cataloged.

4. A CONCEPTUAL MODEL FOR ONTOLOGIES SUPPORTING RESPONSIVENESS IN MANUFACTURING SYSTEMS

To understand how ontologies enhance the responsiveness within the manufacturing system, a conceptual model based on three main axes of analysis is proposed and shown in Figure 1:

A. The **supported function**, which represents the different fundamental features played by ontologies in the context of modern manufacturing processes.

B. The **application** of the ontology, which refers to the specific type of system in which the ontology is implemented, elucidating the functionality of the ontology within that system based on how it is integrated into a particular context.

C. The **contribution to responsiveness** achieved through the ontology, defined as the impact of ontologies in improving a system's capability to respond quickly and efficiently to dynamic changes within the manufacturing environment.

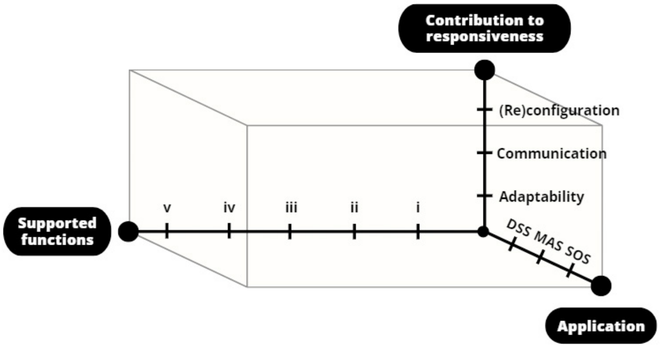

Figure 1. Conceptual model.

Ontologies contribute to different aspects relevant to modern manufacturing processes, as explained by Nagy, Ruppert and Abonyi (2021). Five of them are related to responsiveness:

i. Data processing, structurization, and interoperability: it signifies the extent to which the concept handles and processes data, ensuring structured information and promoting interoperability among different components in the manufacturing processes.
ii. Modelling of manufacturing processes: it reflects the involvement in modelling various aspects of manufacturing processes, representing and structuring information related to the processes involved in manufacturing.
iii. Information sharing: it denotes the degree to which the concept facilitates the sharing of information among different entities or systems in the manufacturing sector.
iv. Knowledge representation: it indicates the extent to which the concept is utilized to represent and structure knowledge in a way that is beneficial for decision-making and understanding processes within the manufacturing domain.
v. Process planning: it reflects the involvement in the planning and coordination of manufacturing processes.

Once identified the supported functions of each application, the conceptual model further categorizes key concepts on the application of ontologies in the manufacturing sector. These concepts, described by Cheng et al. (2016) showcase the different applications that ontologies play in enhancing different aspects of manufacturing systems. The three categories utilized for classification are:

- Design Support Systems (DSS), which refers to systems where ontologies are used to structure knowledge and provide a shared framework for organizing information during the design and integration of processes, quality control and production planning.

- Multi-Agent Systems (MAS), which refers to distributed systems composed of autonomous agents that focus on the coordination, planning and scheduling of production activities, using ontologies as a shared vocabulary for their communication.

- Service-Oriented Systems (SOS), which refers to systems relying on ontologies to enable interoperability and dynamic integration of services, particularly in Internet of Things (IoT) or cloud-based manufacturing environments. In these systems, manufacturing resources are made available as semantic web services, with ontologies describing them in a machine-readable way, allowing automatic discovery, composition, and contributing to resource sharing and reuse across heterogeneous applications and systems.

It is also essential to explore the impact of ontologies in enhancing the company's responsiveness. In this context, the utilization of ontologies in manufacturing processes is observed to contribute to responsiveness in three specific ways, that emerge from the analyzed literature results:

- Supporting the adaptation to dynamic environments: in a rapidly changing manufacturing setting, systems need to adapt to dynamic conditions, including changes in market demands, product designs and external factors.
- Facilitating efficient data and information sharing: effective data and information sharing is crucial for seamless collaboration among different components in a manufacturing environment to improve coordination and decision-making.
- Supporting rapid configuration and re-configuration: the ability to quickly configure and reconfigure production systems is essential for responsiveness, especially when dealing with changes in product requirements, resource availability, or market demands.

5. A COMPREHENSIVE EXPLORATION OF ONTOLOGIES SUPPORT FOR RESPONSIVENESS

The conceptual model proposed within this work, which allows to describe how ontologies contribute to responsiveness of manufacturing systems through different supported functions and applications, is applied to describe the different documents collected.

Table 1. Application and supportive functions of ontologies in manufacturing and their contribution to responsiveness.

	Supported functions					Applications			Contribution to responsiveness		
	i	ii	iii	iv	v	DSS	MAS	SOS	Adaptability	Communication	Configuration
Yinmin, G. and Ruixue, F. (2009)	X		X	X			X			X	
Leitao, P. et al. (2012)	X	X	X	X			X			X	
Meridou et al. (2015)	X	X		X	X		X		X		
Negri et al. (2015)	X	X	X	X		X			X	X	
Järvenpää et al. (2017)		X		X	X	X					X
Järvenpää, Lanz and Siltala (2018)		X		X	X	X			X		X
Ma et al. (2020)		X		X	X	X			X		X
Buckhorst et al. (2022)	X	X		X	X		X			X	X
Reffad and Alti (2023)	X			X				X	X		

Legend:
i. Data processing, structurization, and interoperability
ii. Modelling of manufacturing processes
iii. Information sharing
iv. Knowledge representation
v. Process planning

5.1 *Supported functions*

The ontologies discussed in these studies collectively play a crucial role in semantically representing and structuring knowledge within the manufacturing domain. For instance, the ontology proposed by Yinmin, G. and Ruixue, F. (2009), facilitates semantic interoperability by establishing a shared vocabulary in the domain of supply chain management, enabling heterogeneous agents to consistently interpret terms and meaningfully exchange information. Similarly, in Leitao, P. et al. (2012), the GRACE ontology formalizes the data structure for organizing shared knowledge related to available resources in the production line, product and process models that describe how to produce the products (Leitao and Restivo, 2006). Likewise, in the paper of Negri et al. (2015), the P-PSO ontology (Politecnico di Milano – Production Systems Ontology) has evolved into the Manufacturing System Ontology (MSO), that is a domain ontology for the representation of production systems, which covers the domain of logistics, discrete and process production. Whereas, in ARUM project (Meridou et al. (2015)), ontologies represent knowledge from knowledge-intensive systems such as schedulers and planners: they semantically describe the main aspects of the manufacturing domain, model the current production status, and define entities relevant to events during the production process. Furthermore, Järvenpää et al. (2017) explored the capability matchmaking approach, relying on formal representations of product requirements and system capabilities. However, this method utilizes static resource descriptions that lack a lifecycle perspective, depicting the nominal rather than the real-time capability of resources. This problem, however, is addressed in the paper by Järvenpää, Lanz and Siltala (2018), which presents the development of the Manufacturing Resource Capability Ontology (MaRCO), focused on describing the functional capabilities of manufacturing resources, placing particular emphasis on lifecycle management. In Buckhorst et al. (2022)'s work, instead, ontologies are used to provide a basis for data models in cyber-physical production systems and Holonic Control

Architecture (HCA). The introduction of two intermediate ontologies, HOLonic assembLy manufacturing ONTOlogy (HOLLONTO) integrating cyber-holonic concepts, and FLExible Resource Manufacturing Ontology (FLERMO) merging MASON and MaRCO and holding information related to the physical world, results in the final Line-Less Mobile Assembly System (LMAS) HCA ontology. In Ma et al. (2020)'s paper, ontologies are highlighted for their crucial role in computer-aided process planning systems, specifically in the knowledge-based selection of machining activities and resources. The authors emphasize the creation of a knowledge base using ontologies, along with OWL and Semantics Web Rule Language (SWRL), to develop an ontology-based conceptual model that defines taxonomies, properties, and causal relationships among core concepts like machining features, operations, cutting tools, and machine tools.

Additionally, the ontologies proposed by Järvenpää et al. (2017), by Järvenpää, Lanz and Siltala (2018), and by Ma et al. (2020) show other common elements such as the modelling of various aspects of manufacturing processes and the involvement in their planning and coordination. Järvenpää et al. (2017) propose a capability-based matchmaking procedure that automates the suggestion of resource alternatives for specific product requirements, aiding system designers and reconfiguration planners. The software for this matchmaking utilizes the Capability Matchmaking Ontology, importing both the Resource Model (modelling resource-specific capabilities) and the Product Model (detailing product characteristics and manufacturing requirements). This automated process reduces the workload for system designers and reconfiguration planners by filtering out impossible solutions and suggesting possible alternatives for system design and reconfiguration. In the work of Järvenpää, Lanz and Siltala (2018), the MaRCO model offers methods to formally describe and store not only the nominal capability of a certain resource type, but also the updated information of the resource instances through their use and individual lifecycle in order to provide the planners more insightful information to support their decisions. Instead, the method proposed in Ma et al. (2020) addresses the challenges of manual and time-consuming planning for complex geometries by focusing on multi-level machining feature recognition and knowledge-based selection of machining activities and resources. The developed ontology provides a formal representation of domain knowledge, which facilitates the selection of appropriate manufacturing activities/resources for specific parts, thereby supporting process planning for rotational parts and enabling explicit modeling, management, and integration of knowledge to effectively address rapid changes in product design and market demands. The developed ontology provides a formal representation of domain knowledge, which facilitates the selection of appropriate manufacturing activities/resources for specific parts, thereby supporting process planning to effectively address rapid changes in product design and market demands.

The remaining ontologies similarly share a common function, emphasizing data processing, structurization and interoperability. As exemplified in Reffad and Alti (2023), their study extends the functionality of the Context-aware Quality Cloud Enterprise Resource Planning (CxQSCloudSERP) ontology. One of the main benefits of extending the CxQSCloudSERP is that the business process can be made more flexible and interoperable through richer semantic service information of Internet of Things (IoT) field and Fog capabilities.

The ontology presented in Yinmin, G. and Ruixue, F. (2009) also aims at ensuring data interoperability, in addition to facilitating information sharing. By enhancing the existing information sources with ontology, the agents are able to recognize and understand what a piece of information is and what it is about because the term is officially described in a public ontology.

Furthermore, the ontologies proposed by Leitao et al. (2012) and Negri et al. (2015) share other common supportive functions after the ones mentioned above (i & iv): modelling of manufacturing processes and information sharing. The GRACE ontology, outlined by Leitao et al. (2012), provides a structured framework for organizing shared knowledge and fostering interoperability among agents, specifically designed for agent-based systems that integrate processes and quality control in production lines. Conversely, the MSO ontology, as described by Negri et al. (2015), is designed to facilitate semantic interoperability within a control architecture based on semantically enriched Web Services. It enables the inclusion of semantic content into the control level of devices and applications, thereby enhancing interoperability among devices from different vendors. The proposed solution to the challenges of production system flexibility and agility is achieved by facilitating the rapid reconfiguration and seamless integration of production system elements at the shop-floor control level.

The last ontologies, presented in Buckhorst et al. (2022) and Meridou et al. (2015), also feature shared functionalities, such as modelling of manufacturing processes and process planning. The ontological approach presented by Buckhorst et al. (2022) for implementing the data model has enabled the identification of essential interactions and attributes crucial for agent-based solutions and promotes semantic interoperability. The goal of LMAS HCA is to manage daily business, transforming detailed factory configuration plans and their underlying station configurations into executed assembly orders. Data in ARUM (Meridou et al. (2015)) are transformed into concepts of the core and scene ontologies and sent to the ontology service, which facilitates the integration of services, MAS and legacy systems, enabling communication, monitoring and interoperability essential for managing dynamic manufacturing. Additionally, within ARUM, since schedulers and planners are implemented as MAS, the ontologies ensure precise and explicit semantic representation for effective planning and scheduling.

5.2 Applications

The applications of ontologies within the manufacturing systems reveal diverse implementations classified as DSS, MAS, and SOS. Based on the role in guiding design, enhancing communication among agents, and enabling resource sharing, it is indeed possible to better understand their significance in the applied context.

The concept of DSS can be identified in Negri et al. (2015) where the MSO, used for the control of the production system, is a general taxonomy which can support design, simulation, planning and scheduling, performance assessment and data integration in the manufacturing field. Another case of DSS can be found in Järvenpää et al. (2017), where the approach supports automatic decision-making in reconfiguration planning by suggesting resource alternatives for specific product requirements. MaRCO, instead, in Järvenpää, Lanz and Siltala (2018), enhances the design process by supporting decisions related to reconfiguration, re-use, and maintenance of resources. Its optimization for capability matchmaking underscores its role in providing essential information for the design and integration of manufacturing systems. Moreover, Ma et al. (2020) illustrate the system's use of ontologies to structure knowledge and guide decision-making in manufacturing process planning and design, aligning seamlessly with the characteristics of a DSS.

On the other hand, the system proposed by Yinmin, G. and Ruixue, F. (2009) aligns with MAS principles, leveraging agents to enhance its capabilities and functionality, using the ontology to allow a better communication among them. Simultaneously, the GRACE Ontology, as detailed by Leitao et al. (2012), has been designed to define the knowledge structure within a multi-agent system integrating process and quality control on production lines, particularly for home appliances. Instead, in the paper by Meridou et al. (2015), since users are knowledge-intensive systems such as schedulers and planners, when they are implemented as MAS, the ontology related to ARUM can be introduced to have semantic explicitness, eliminating any possibility of misinterpreting the defined concepts. Additionally, the study conducted by Buckhorst et al. (2022) leverages the ontology for cost estimation within the context of MAS. Here the proposal to employ the HCA and the concept of "holon" can categorize this approach as MAS. The HCA further grants autonomy to entities in the LMAS, allowing for spatio-temporal reconfiguration of factories and stations.

Furthermore, the study by Reffad and Alti (2023) showcases the SOS since it proposes a method to discover services relevant to customer needs while selecting services with high quality of service and optimal energy cost and provides a continuously optimized composite service based on context changes and/or customer preference changes.

5.3 *Ontologies contribution to responsiveness*

The discussion of the supported functions and application of ontologies permits to understand how these ontologies contribute to enhancing the responsiveness within the manufacturing context.

The ontologies that allow to reach high adaptability and responsiveness to dynamic environments are presented, for example, in Meridou et al. (2015) as solutions enabling efficient coordination of decision-making processes in knowledge-intensive systems. Correspondingly, Negri et al. (2015) propose an ontology as a solution addressing production system flexibility and agility by facilitating more rapid reconfiguration and easier integration of production system elements at the shop-floor control level. This is achieved through the inclusion of semantic content into the control level of the devices and applications. Through the developed ontology, the service-oriented control architecture can be automatically configured thanks to the continuously updated ontological content, ensuring agility and responsiveness to changes in requirements and circumstances. Additionally, Järvenpää, Lanz and Siltala (2018) introduce MaRCO, which allows detailed capability descriptions of evolving resources used in the factory floor. It offers the updated information of the resource instances through their use and individual lifecycle, enhancing responsiveness and providing planners with insightful information to support decisions. The extension of the CxQSCloudSERP ontology by Reffad and Alti (2023) includes industrial IoT concepts, contributing to the dynamic adaptation of smart enterprise resource planning systems to the usage contexts of IoT, fog computing, and cloud computing. Ma et al. (2020) propose an approach based on machining features and ontology to support the process planning of rotational parts in order to deal with the rapid change of product design under different market demand.

The facilitation of efficient communication, instead, can be identified in Yinmin, G. and Ruixue, F. (2009), which present an ontology that defines a common vocabulary for agents to communicate with one another. In this case, the ontology performs two tasks: communication protocol and enhancing precision of retrieving information. Conversely, Leitao, P. et al. (2012) introduce an ontology to organize the knowledge related to the available resources facilitating shared and exchanged knowledge between the agents. Indeed, the ontology is designed to integrate process and quality control in production lines. Similarly, Negri et al. (2015) utilize MSO for semantic interoperability within a control architecture, enabling communication between embedded systems and open standards. The creation of the agents in the study proposed by Buckhorst et al. (2022) involves complex cooperative communication structures for a significant number of entities: HOLLONTO and FLERMO ontologies are utilized to support data models within cyber-physical production systems and HCA, enhancing flexibility and adaptability.

Within the papers analysed, several ontologies that support the configuration and re-configuration of production systems have been identified. For instance, Järvenpää et al. (2017) and Järvenpää, Lanz and Siltala (2018) present a capability-based matchmaking procedure that eases the system design and reconfiguration planning and facilitates the reactive adaptation by automatic decision support. The ontology proposed by Järvenpää, Lanz and Siltala (2018) provides the planners more insightful information for decisions on the reconfiguration, re-use, and maintenance of the resources. Moreover, Ma et al. (2020) address the time-changing manufacturing resources in enterprises, significantly enhancing production efficiency and responsiveness by automating the process planning. Buckhorst et al. (2022) propose the LMAS cyber-physical HCA, enabling possibilities for the spatial (layout) and coincidental temporal reconfiguration (schedules) of (partially) automated mobile or mobilized adaptive (multi-purpose) resources.

6. Conclusions

This paper represents one of the first attempts to systematically investigate how ontologies improve responsiveness in the manufacturing domain. Based on a structured literature review and the analysis of nine specific examples, the findings underscore how the application of ontologies enables manufacturing systems to adapt to dynamic environments, support efficient communication, and facilitate the rapid configuration and reconfiguration of production processes.

The contributions of this study are twofold: (1) the development of a conceptual model that enables the classification and comparison of different ontology-based approaches, and (2) a structured map of the current knowledge, showing how such approaches contribute to core responsiveness aspects. Together, these results offer both a descriptive synthesis and a practical lens for guiding future studies and implementations efforts in manufacturing systems aiming for higher adaptability and responsiveness.

Future research should address the integration of ontological models in manufacturing systems, as they evolve to become more intelligent and adaptable. Ontologies support the creation of interconnected machine networks, that foster agile responses to dynamic shifts in demand, supply chain variations and unforeseen disruptions.

Nonetheless, it is important to acknowledge the limitations of this research. In particular, relevant studies that employ alternative terminology to describe responsiveness may have been excluded from the analysis. Despite the limitations, this paper highlights the applications and contributions of ontologies in responsive manufacturing, providing valuable insights for researchers, practitioners, and industry professionals to delve deeper into this dynamic field.

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