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An ontology-guided approach to process formation and coordination of demand-driven collaborations

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ABSTRACT

Demand shocks and fluctuations underscore the need for new approaches to coordinate collaboration between firms to scale up production. This paper proposes an approach to formalise product and process requirements via a collaboration ontology and applies semantic reasoning techniques for process formation. Our approach contributes to production research by providing flexibility in coordinating firms engaged in demand-driven collaboration. The proposed approach has four core dimensions: (1) The Collaboration ontology builds on a set of product assembly requirements, process steps, their input/output resources and semantic rules; (2) the ontology reasoner derives resource dependencies between the steps; (3) the java tool interprets resource dependencies as possible transitions in Business Process Management Notation (BPMN); (4) a workflow engine executes the generated product assembly process. The approach and the ontology were validated in an industrial aerospace tendering scenario demonstrating its practical relevance for firms seeking demand-driven collaborations to react to production changes. Finally, we position and explain our contributions to the body of knowledge in collaborative production engineering.

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Collaboration process design; ontology; process coordination & reasoning; production systems design; industry 4.0

1. Introduction

European low-volume high-variability manufacturing industries, such as aerospace manufacturing, contend with demand fluctuations and thus increasingly seek novel ways to support demand-driven collaboration between the supplying firms. During the last 15 years of production and supply chain transformation, Airbus has reduced direct supply relationships with more than 6,000 multi-tier suppliers in favour of risk-sharing partners (Bernhard et al. 2007; Janke et al. 2007; Rossen et al. 2015), increasing reliance on large supply chain companies (system suppliers), as depicted in Figure 1. Small and Medium-Sized Enterprises (SMEs) in the aerospace industry are highly-specialised firms that need partnerships to deliver materials, standard parts, and support services to any supply chain tier (SCE 2017). However, they often cannot act as suppliers due to capacity or capability constraints and must form partnerships to bid for work (Schirrmann and Drat 2018). SMEs increasingly look for new collaborations to get more work; however, the inertia of established buyer-supplier relationships and process challenges associated with integrating new companies into a supply chain pose steep barriers for SMEs to join new demand-driven collaboration opportunities (Schirrmann and Drat 2018; Turkina, Van Assche, and Kali 2016). Particularly, SMEs perceive factors impeding data sharing and coordination as significant roadblocks to demand-driven collaboration (Kazantsev et al. 2022). To tackle some of the stated challenges, this paper studies the application of semantic technologies, such as ontologies and automated reasoning, to facilitate process formation and coordination of demand-driven collaborations between supplier firms and help larger firms to scale up their production capacities. We position our research (including the semantic model and its implementation) as a contribution towards supporting the transition between a centralised and a distributed supply chain setting and developing artefacts to support SMEs to fully engage in future distributed supply chains, as illustrated in Figure 1. We used the European Aerospace industry development as a context for this investigation. In particular, we worked on two large-scale projects: Decentralised Agile Coordination Across Supply Chains[1] (2016–2019), and European Connected

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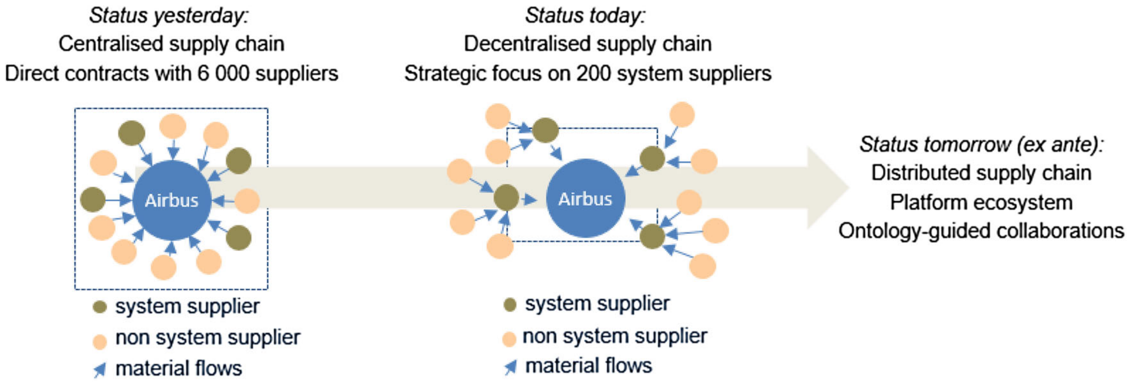


Figure 1. The changes in the aerospace industry require ontological support for demand-driven collaborations.

Factory Platform for Agile Manufacturing[2] (2019–2022), in a research partnership with the largest supplier cluster to Airbus — The HANSE Aerospace cluster.[3]

Our work on demand-driven collaboration contributes to the vision and research agenda of Industry 4.0 (Ivanov et al. 2020; Kagermann et al. 2013; Machado, Winroth, and Ribeiro da Silva 2020; Smit et al. 2016), in particular, in topics revolving around the integration of production processes along the entire value chain (Kagermann et al. 2013; Moeuf et al. 2018). Future industry value chain predictions envision more distributed supply structures eventually replacing hierarchical supply chains (EY 2020). These predictions call for eliminating barriers to demand-driven collaboration across supply chain tiers as a solution to quickly respond to the fluctuating demand for products with high quality and affordable costs. However, despite the importance of approaches to support increases in the pace of industrial transformations, few studies investigate the phenomenon of demand-driven collaboration in production management (Ivanov et al. 2020; Ivanov, Das, and Choi 2018; Ivanov, Dolgui, and Sokolov 2019; Olsen and Tomlin 2020; Tang and Veelenturf 2019), and even a smaller number of studies consider SMEs in the scope of other suppliers (Mittal et al. 2018; Moghaddam and Nof 2018; Panetto et al. 2019). These gaps underscore the importance of finding novel ways to support collaborative product assembly, engaging most supply chain participants, such as SMEs. The innovation and added value created by a long tail of small suppliers collaborating across supply chain tiers can play an essential tactical production role, for example, in fulfilling specialised low-volume jobs such as furnishing aircraft interiors tailored to a specific flag carrier; and complementing overall production capacity when dealing with sudden changes in the volume of orders (order fluctuation).

An ontology is 'an explicit specification of a shared conceptualisation' (Gruber 1995, 908). Related technologies for automated reasoning are suitable approaches to coordinate interactions between supply chain firms. However, they have not fully realised their potential in operations research compared to computer science and information systems domains. Applying knowledge representation mechanisms to manage global production networks' complexity will become mainstream and drive productivity gains in manufacturing. 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 automated team, product, and process composition (Cisneros-Cabrera et al. 2021; Liu et al. 2022), resource management for aerospace manufacturing (Arista et al. 2022), aircraft manufacturing system design (Arista et al. 2023) and Reconfigurable Manufacturing System design (Arista et al. 2023). Further semantic technologies and related tools may support the exploration of the broader field of collaboration design. The work reported in this paper tackles the following research question:

> RQ: 'How to support demand-driven collaboration using semantic technologies for manufacturing process formation and coordination?'

To answer the RQ, we build on ideas from Collaboration Engineering (CE) — a well-established practice of coordinating repeatable group work of domain experts without the ongoing support of external facilitators (Briggs et al. 2013; De Vreede and Briggs 2019). Such group work employs a logical model of collaboration, including key concepts, relations, and inter-dependencies (Knoll et al. 2010) to tackle the uncertainties of 'not-so-well-structured [collaboration] settings' (Kolfschoten and De Vreede 2009). Notably, we adopt the lens of coordination theory (Crowston 1997; Malone and Crowston 1990) to manage resource dependencies between actors, resources and process steps and execute a collaboration process guided by the collaboration ontology. The advantage of an ontology for production settings is that it provides machine-readable inter and intra-organisational information exchange mechanisms enabling the standardisation of production resource interfaces, information flows, and the automation of governance rules to guide available process steps to support the enactment of manufacturing goals (e.g. call for tender in production). The process is triggered by a tendering event/goal and involves process mapping and allocating resources complying with dependencies and constraints.

This paper contributes to production research with an approach to coordinate production in response to a new specific order in low-volume high-variability manufacturing, such as aerospace manufacturing. It is an extension of the conference paper Kazantsev et al. (2022), which briefly presented an ontology-guided approach for coordination; and Kazantsev (2022) – a PhD thesis that conceptualised the idea for supporting demand-driven SME collaborations. A key innovation of our approach is using an ontology to guide production process formation and coordination of demand-driven collaboration. First, we use a product data model, such as a Bill of Materials (BOM) (Vanderfeesten, Reijers, and Van der Aalst 2011), to derive product assembly requirements, such as hierarchical relationships between semi-parts, resource needs and production steps. These elements are implemented into an ontology as classes and properties. Second, we use the Web Ontology Language (OWL) and the Semantic Web Rule Language (SWRL)[4] to define rules that convert resource requirements between process steps as dependencies. Third, we interpret these dependencies as potential ways to link the process steps together using the BPMN notation, such as swim lanes, tasks, logical elements, and events. Fourth, we develop a web prototype[5] to demonstrate how the derived process will serve as an input to a workflow engine. The ontology-guided approach makes production processes more transparent and flexible by guiding process assembly, which can be applied to various industries. The dimensions of the ontology-guided approach are illustrated in Figure 2.

This paper is organised as follows: Section 2 presents the background of this study. Section 3 outlines the research methodology. Section 4 presents key findings, including the ontology and the approach to process formation & coordination. Section 5 summarises research results and outlines managerial implications, limitations, and future work.

2. Background and related work

2.1. Interoperability in production research

Interoperability is '[an] ability of systems [of companies] to understand functionalities of each other' (Chen, Doumeingts, and Vernadat 2008). Earlier work focusing on interoperability for industrial production resulted in developing the European interoperability framework, followed by initiatives in the context of Industry 4.0, notably the Reference Architectural Model for Industry 4.0 — RAMI (Schweichhart 2016). Although interoperability is considered one of the critical principles of Industry 4.0 (Smit et al. 2016), the existing literature on Industry 4.0 adoption identifies interoperability as one of the critical concerns for SMEs (Kazantsev et al. 2018; Sampath and Hegde 2013). When manufacturing SMEs attempt to collaborate and form a new supply relationship, the coordination of work, the integration of processes and systems, and the compliance with industry governance rules pose new interoperability challenges. Existing workflow management and industrial process management tools are limited in their support for new ad-hoc collaborations created *on demand* based on rapidly changing production requirements since, in most nascent collaboration process design scenarios, the semantics of information and material flows cannot be specified in advance. A key interoperability challenge is enabling partners' information systems to process and infer meaning from the business collaboration concepts (e.g. client, product, semi-part, goal, activity, and others).

Semantic technologies such as domain ontologies have been proposed to address industrial collaboration interoperability challenges. The Top-Level Ontology (TLO) is 'an ontology created to represent the categories shared across a broad range of domains' (ISO 21838-1:2021). For example, TLO supports digital twin interoperability (D'Amico et al. 2022). OntoCommons[6] is a European project dedicated to standardising data documentation across all domains related to materials and manufacturing. Mainly, OntoCommons works with TLOs: BFO, DOLCE, and EMMO. Industrial Ontologies Foundry Core (IOF-Core[7]) is another example of an organisation that is trying to gather mid-level ontologies aligned to BFO (ISO 21838-2). Although the domain-neutral Top-Level Ontologies (TLO), or foundational ontologies, can support any domain by definition, they lack specific

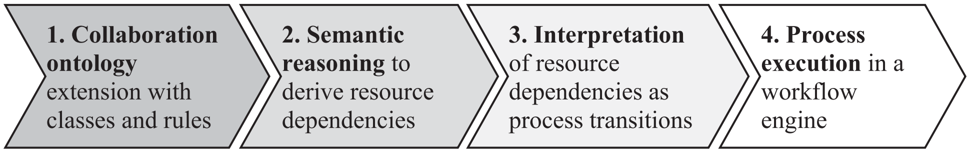


Figure 2. Ontology-guided approach to process formation and coordination.

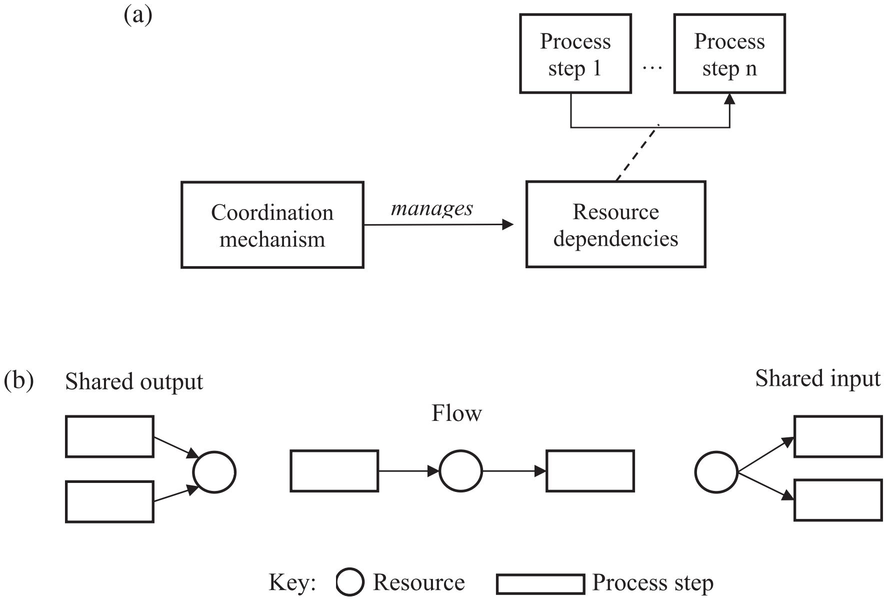


Figure 3. a. The coordination framework for managing resource dependencies between process steps (Lee, Wyner, and Pentland 2008). b. The resource dependencies between process steps (Malone and Crowston 1994).

domain knowledge, such as classes, properties and rules; therefore, they need to be extended by the mid-level ontologies. For example, IOF is creating such mid-level ontologies: IOF Core and an ontology for Supply Chain[8], yet this work does not fully cover the domain of demand-driven collaborations in manufacturing, characterised by dynamism and flexibility.

2.2. Coordination theory

Coordination theory (CT) studies how actors perform interdependent activities to achieve goals (Crowston 1997; Malone and Crowston 1990), i.e. to manufacture a product. Processes consume and produce resources (semi-parts and products) and have resource *dependencies* (Lee, Wyner, and Pentland 2008). To manage these dependencies, responsible actors apply coordination mechanisms (Crowston 1997), depending on the related context (Crowston, Rubleske, and Howison 2015). While *production process steps* must be executed to satisfy production requirements, coordination mechanisms are secondary to resolving inter-dependencies between them, Figure 3a.

The theory distinguishes resource dependencies: 'flow', 'shared input' and 'shared output', which require different coordination mechanisms. 'Flow' dependency implies that the resource must be produced when needed (issued notification for the consumer), usable (e.g. standardised, tested), and available for a consumer (i.e. transferred to the consumer). 'Shared input' stipulates that two or more actors require the same resource, and someone must prioritise resource allocation. Finally, 'shared output' happens when two or more actors collectively develop a resource. A coordination mechanism for this dependency is either (a) to pick one activity or (b) to arrange iterations between these activities (once activities add value to the product), as depicted in Figure 3b.

2.3. Ontology as a model and contract for collaborations

Process taxonomies and ontologies can structure design knowledge and resolve unmanaged or partially managed dependencies (Crowston 1997; Malone and Crowston 1994). Ontologies are formal representations of conceptualisations of domains of interest; conceptualisation is an abstract, simplified view of some knowledge we wish to capture (Greco et al. 2004; Gruber 1995). A typical ontology consists of typed objects (nodes) and properties (links), where the meaning is explicit and enables reuse, revolutionising how large organisations utilise and share their data (Noy et al. 2019). An advantage of formal semantics is that it enables automated reasoning: (1) Determines whether an ontology is consistent and fits the guidelines and (2) Infers additional information based on the axioms that define the ontology. Semantic technologies increase software quality and reusability by eliminating the programming logic needed for semantic processing and inferencing from being hardwired into application software code. By deriving knowledge from the domain, the specification of the production process can be automated (Greco et al. 2004; Rajsiri et al. 2008) to conceptualise manufacturing resource exchange of plants (Lin et al. 2011), simulate logistics (Jiang, Peng, and Liu 2010), or even whole supply chain management (Yan et al. 2010).

2.4. Research gap and contribution

Semantic and knowledge-based technologies, such as ontologies and automated reasoning for distributed decision support across multiple local instances, support a promising way to create a collaboration process between firms on demand and resolve coordination problems. By applying knowledge-based tools, we can manage the complexity of production networks, transforming conventional buyer-supplier contracts into flexible, demand-driven sourcing relationships (Benitez, Ayala, and Frank 2020; Schmidt et al. 2021).

However, previous works partially explore these ideas, not including ontology implementation and the corresponding process assembly system guided by ontology (Dourish et al. 1996; Vanderfeesten, Reijers, and Van der Aalst 2011). The established ontologies in the manufacturing domain focus on integrating cross-organisational systems; however, to our knowledge, they mainly deal with encoding pre-defined collaboration process structures. Therefore, the research efforts have yet to develop the notion of ontology-guided demand-driven collaborations fully. By deriving resource exchange across manufacturing supply chains (Lin et al. 2011), the proposed approach derives resource dependencies between the process steps to construct and coordinate process execution. This solution can also simulate collaborative processes involving alternative team compositions (Jiang, Peng, and Liu 2010), spanning several supply chain tiers or across supply chains (Yan et al. 2010). Ontology-guided coordination could help firms better react to market demands (Horváth and Szabó 2019) and utilise capacities in the case of disruptions.

Our solution also contributes to potential standardisation efforts aimed at cross-company processes and data exchanges focusing on industrial collaborations (Müller, Veile, and Voigt 2020). Furthermore, due to the need to support the efforts of the ontological community, such as IOF, in developing a supply chain domain ontology, we propose our approach as a generic mechanism that can be incorporated into any supply chain ontology for converting classes and properties describing material flows into a process ready for execution in the workflow engine.

3. Methodology

3.1. Research context

The findings reported in this paper originate from research conducted in the context of a large-scale Industry 4.0 digital manufacturing project funded by the European Union under the Horizon 2020 research and innovation programme (grant agreement no. 723336) to help small innovative suppliers to integrate into aerospace supply chains and traditional industrial processes. The DIGICOR (Decentralised Agile Coordination Across Supply Chains) project[9] involved a consortium of 11 organisations from Germany, the Netherlands, Greece, the United Kingdom, the Czech Republic, and Italy, encompassing an Association of Aerospace SMEs (AAS) and a significant aerospace corporation (MAC). The goal of DIGICOR was to develop an open platform, tools, and services for the setup and coordination of production networks to facilitate the collaborative integration of non-traditional yet innovative SMEs into the supply chain of large manufacturers (OEMs). The main production scenario driving the development of an ontology-guided approach involved low-volume and high-variability manufacturing of highly complex products such as modules of commercial aircraft. These outputs are further developed in the – EFPF (European Connected Factory Platform for Agile Manufacturing).[10]

For requirements management, we used the following data collection techniques: (i) paper-and-pencil interviews with 17 CEOs of SMEs representing a spectrum of aviation and space-oriented service SMEs; (ii) in-depth interviews with two industrial experts from MAC and AAS, who had more than 20 years of experience in the aerospace industry; (iii) presentations with discussions during the leading experts in aerospace manufacturing (e.g. project workshops 2017–2019 in Prague, Hamburg and Brussels); (iv) participation in the round tables organised by AAS and MAC at the world's leading event for airlines and aerospace supply chains, such as 'International Supplier Expo Aircraft Interiors 2018-2019. All data was transcribed from the audio recording of the meeting. We used thematic analysis, a qualitative method, to find common themes in the dataset (Braun and Clarke 2006). The analysis of data and requirements unveiled barriers impeding data sharing and coordination between SMEs as significant roadblocks to demand-driven collaboration (Kazantsev et al. 2022), which could be improved by collaboration process support, as shown in Table 1.

We used these three barriers to guide the design goals for developing an ontology to support coordination between the firms. Notably, the high costs of data interchange with customers (Barrier 1) suggest the need for shared processes between suppliers enabling interoperability and information sharing and reducing the time needed to establish data exchanges in a demand-driven collaboration. Creating such an environment can also respond to Barrier 2 by increasing the ability to utilise partners' data, awareness, and earlier mitigation of risks. Finally, Barrier 3 may be resolved by enforcing interoperability between the firms engaged in demand-driven collaborations.

Table 1. The thematic analysis (excerpt) about coordination barriers (Kazantsev et al. 2022).

Overarching Theme	Barriers	N	Representative proof quotations
Barriers impeding data sharing and coordination	1. Costs of data sharing with customers	6	*‘direct IT interface to the [OEM] systems’* [is limited], *‘time-consuming calibration because of missing knowledge for operating devices of customers’.*
	2. Lack of ability to utilise partners’ data	7	*‘unfit technological delivery specifications’, ‘missing standards and interfaces in communication’, ‘proprietary IT systems without adequate standards for data transfer’, and ‘optimisation in information flows and communication for structured data exchange.’*
	3. Cost of lack of coordination	30	*‘Chinese whispers effects in communication’, ‘long production cycles of suppliers* [shift] *estimated delivery time and* [therefore] *delivery requirements of customers* [are getting] *not compatible.’*

3.2. Research method

The design science research method (DSRM) (Hevner 2007; March and Smith 1995) from the Information Systems field was followed to develop the research artefacts and findings reported in this paper. DSRM is gaining popularity in the operations and supply chain fields of study due to its methodological support for constructing processes and optimisation approaches. DSRM is suitable when developing an equally valuable artefact for research and practice (Gregor and Hevner 2013; Hevner 2007). DSRM advocates for multiple iterations with the end-users informed by theoretical underpinnings, which reduces the mismatch between designed artefacts and end users’ expectations for functionality and quality. DRSM (March and Smith 1995) directed the research steps addressing the proposed research question and facilitated the construction of purposeful artefacts – the approach, the ontology, and the process assembly and inference engine implemented using SWRL rules to form a collaboration process. During the research method execution, we often switched between collecting production requirements (relevance cycle), elicited in collaboration with the aerospace SME cluster and investigating the gaps and theoretical underpinnings for our designs (design cycle) in the extant literature (rigour cycle). The main research steps are positioned as cycles, depicted in Figure 4:

- The *Relevance cycle* collected requirements from the EU-funded project DIGICOR (2016-2019) for developing an ontology-guided approach. Requirements for the ontology have been analysed, and reuse has been sought from existing ontologies. We started with the early experimentation with available top-level ontologies but then realised the need to develop a solution that could be incorporated into any ontology with classes and properties specifying processes and resources. Mainly, we built upon the Enterprise Ontology (Uschold et al. 1998), the Collaboration Ontology (CO) (Mehandjiev, Stalker, and Carpenter 2008), the ontology for small series production by (Inden et al. 2013, 158) and the Process model ontology (DeBellis and Neches 2022, 1062). We extended the ontology for small series production by (Inden et al. 2013, 158) by incorporating process steps, resources and SWRL rules. We drafted an interactive dashboard[11] to engage with the SME cluster managers to explain the interface of the solution and get feedback. The assembly

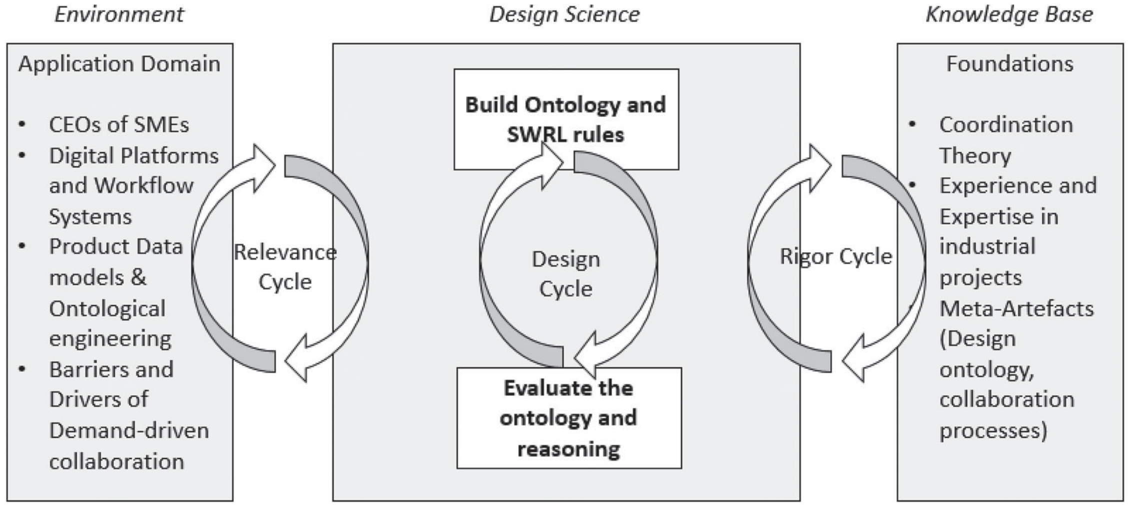


Figure 4. Design Science process, adapted from (Hevner 2007).

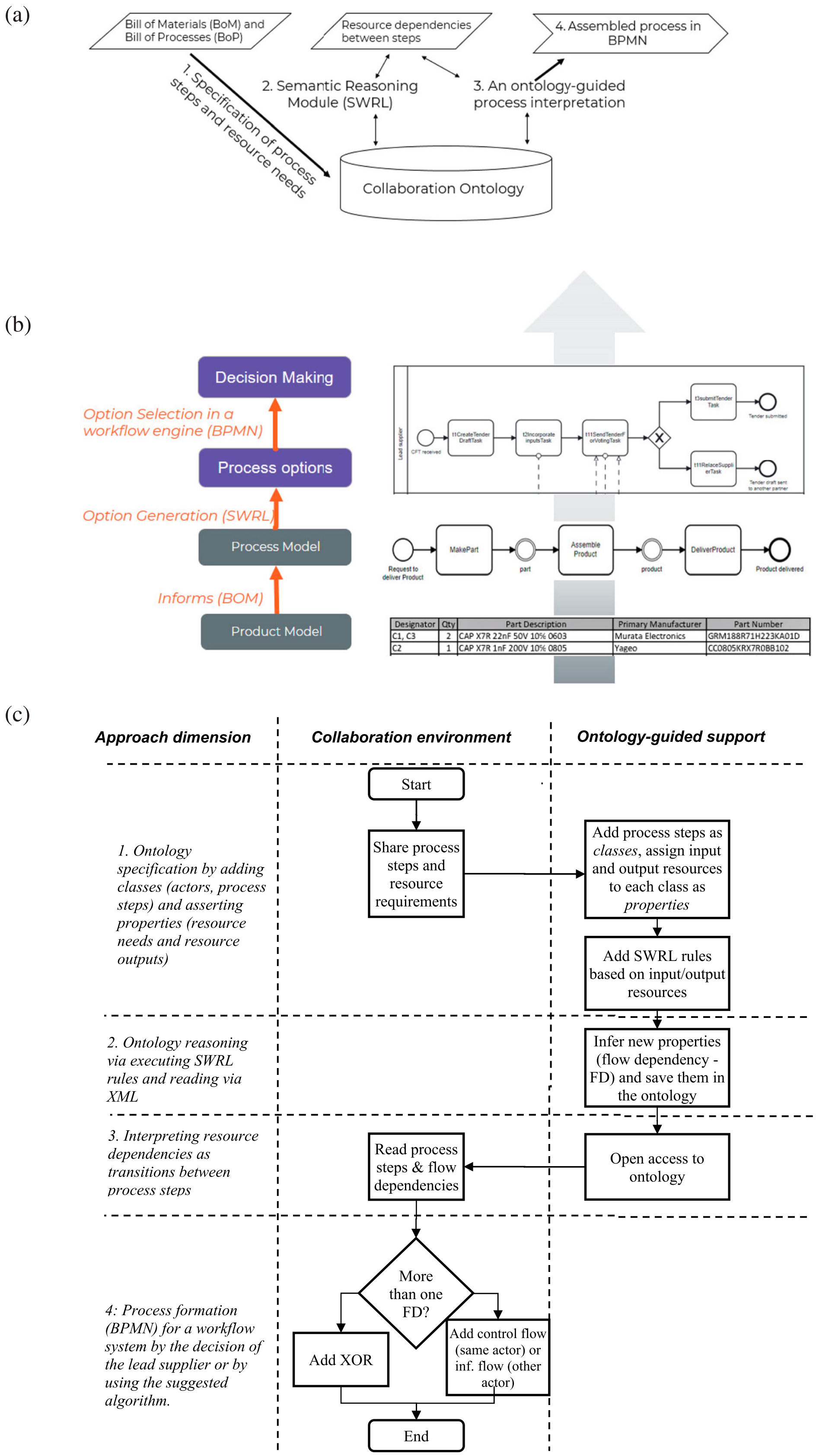
design inherited features from the Supply Chain Operational Reference (SCOR/DCOR) model, especially embedding the key Level-1 processes.

- The *Design cycle* enabled the iterative development of the ontology-guided approach. Using coordination theory (Malone and Crowston 1994), we asserted input and output resources as properties for each process step, not the sequence between the steps *per se*. (This contrasts with the former ontology (DeBellis and Neches 2022), which directly mapped the 'Next' property between two process steps, making connections static). We made several iterations of ontology development (as part of the design cycle), including validating the ontology with the end users. This validation guaranteed that the ontology requirements were met and that the ontology-guided approach to supporting coordination answered the RQ, making process formation and coordination flexible and dynamic. Thus, the proposed artefacts addressed a real business problem – how to support demand-driven collaborations in production (Kazantsev et al. 2022).
    (1) ○ *Comparison with the established ontologies*: To show the advantages of our design and compare it with extant literature, we identified only one comparable ontology for a similar domain, proposed by (Inden et al. 2013); however, this ontology does not allow the construction of a coordination process via reasoning. In contrast, our ontology constructs a sequence of steps using resource dependencies between process steps, a unique contribution to flexibility in B2B collaborations. The proposed ontology described in this paper extends earlier work on mapping semantic links to process steps (DeBellis 2019) by incorporating constructs derived from coordination theory;
    (2) ○ *Checking for inconsistencies*: The authors completed a Bunge-Wand-Webber checklist[12], one of the most popular methods for constructing valid ontologies (Lukyanenko 2020). OWL has formal semantics, a decidable subset of First Order Logic (FOL); therefore, we checked for logical inconsistencies using an automated reasoner (DeBellis and Neches 2022). In addition, we used one of the ontology testing tools called the OntOlogy Pitfall Scanner (OOPS)[13],[14] (Poveda-Villalón, Gómez-Pérez, and Suárez-Figueroa 2014), which is a tool capable of identifying 'anti-patterns', i.e. these issues may indicate the ontology does not follow accepted best practices, and that the reasoner will not catch (DeBellis and Neches 2022). For example, through OOPS, we found that there was a need for an Open Source licence on the ontology (therefore, the CCA 4.0 licence was added). Other minor changes included prefixes, domains or ranges for object properties, data properties, and redundant superclass removal;
    (3) ○ *Data (ontology) sharing*: we uploaded the ontology to Web Protege[15] and enabled link sharing, so anyone with a link can access the inferred version and provide feedback. The ontology was shown at the thematic session devoted to 'Ontology-Based Development of Industrial Systems' at the MIM 2022 conference and was highlighted by the session's chairs – experts in aerospace ontology engineering.
    (4) ○ *Receiving feedback from the industry*: From the words of the SME cluster managers, We drafted a collaborative tendering in BPMN and compared our ontology-guided results to the suggested one, removing the algorithm so that it derives the correct elements.[16]
- The *Rigour cycle* used the notion of resource allocation as a basis for coordinating process execution (Crowston 1997), which provided a theoretical foundation for this study. Our design allows process steps to be dynamically configured by specifying resources needed for their coordination. We resolved resource dependencies by applying coordination mechanisms and facilitating demand-driven collaborations. Iterations with the existing literature and domain knowledge (rigour cycle) enabled us to fill gaps in the theory, as illustrated in Figure 4.

4. Findings

The suggested ontology-guided approach consists of four steps. First, the product and process specifications are derived from the Bill of Materials and the Bill of Processes. They are asserted as classes and properties of the collaboration ontology, which builds on product assembly requirements, process steps, input/output resources, and semantic rules. Second, the semantic module interprets resource requirements as suggested links between process steps. Third, the semantic links between the process steps are interpreted as a potential process by converting the chunks of classes connected into the BPMN notation. The control flows, and logical junctions (AND, XOR) are specified based on resource dependencies. Fourth, the newly generated process is uploaded to a workflow engine. Figure 5a shows the conceptual model of the proposed approach.

Figure 5b shows a technical model of how the Bill of Materials is used in the ontology to derive a process in the BPMN notation. Specifically, we show the ontological layers (left) that indicate the abstraction levels of



Designator	Qty	Part Description	Primary Manufacturer	Part Number
C1, C3	2	CAP X7R 22nF 50V 10% 0603	Murata Electronics	GRM188R71H223KA01D
C2	1	CAP X7R 1nF 200V 10% 0805	Yageo	CC0805KRX7R0BB102

Figure 5. a. The conceptual model of an ontology-guided approach to process formation. b. The technical model of an ontology-guided approach to process formation. The grey blocks reflect ontological parts, and the blue areas – are process parts. A process is derived from the resource dependencies to deliver a product, as guided by ontology. The figure shows the technical model of an ontology-guided approach to process formation, that interconnects the bill of materials via ontology to process formation and execution. c. A flowchart of how the ontology can 'operationalise' product delivery. The figure shows a flowchart of ontology operationalising product delivery.

these changes. The right part shows that the table (Bill of Materials) is fed to the ontology, structured as Make-Assemble-Deliver classes, and derives a process for the team selected to fulfil a manufacturing order. This proposed approach is closely related to the SCOR model and supports demand-driven collaborations between supply chain members.

Figure 5c displays an algorithm referring to guidance that the ontology provides for a collaboration process between firms, represented as an entity of the Actor class. The Process steps can be asserted to actors, thus, creating conditions for a process formation. The algorithm's outcome (an assembled BPMN process) can be executed in major workflow engines.

4.1. Dimension 1: ontology specification: classes and properties

First, following the Supply Chain Operation Reference model (SCOR), we divided the Bill of Processes into three process steps sub-classes:

- `MakePart` process steps have no input resources and can trigger process formation. Their outputs (parts) are inputs to `AssembleProduct` processes.
- `AssembleProduct` process steps consume input resources (parts or products) and produce output resources (product), thus iteratively developing the product.
- `DeliverProduct` process step consumes the ordered product (per BoM/BoP) as an input resource and ensures product transfer to the customer according to procurement specifications and quality checks.

Second, following Coordination Theory, we *asserted properties* specifying resources which can be produced by other processes belonging to the Collaboration members (for example, a lead supplier or partner):

- `hasInputResource` specifies resource needs (input) per each process.
- `hasOutputResource` specifies the outputs of each process.

4.2. Dimension 2: ontology specification: SWRL functions to infer resource dependencies

In contrast to the asserted properties added manually, the SWRL functions automatically add new properties between the process steps (classes) by checking the resource dependency between the steps (e.g. flow, shared input, or shared output). Thus, the *inferred* properties are derived from the ontology based on the asserted connections.

The first SWRL rule (1) infers the `hasFlowDependency` between two process steps – `'?TaskA'`[17], producing a resource and `'?TaskB'`, requiring the produced `'?resource'`. However, due to the Open-world assumption, OWL does not assume that two objects are different unless there is some axiom that implies they must be. Therefore, we specify that for `hasFlowDependency`, process steps need to be distinct `(differentFrom)`:

```
hasOutputResource (?taskA, ?resource)
  ^ hasInputResource (?taskB,
  ?resource) ^ differentFrom(?taskA,
  ?taskB)
-> hasFlowDependency (?taskA, ?taskB)
                                      (1)
```

The second SWRL rule derives how the ontology supports inference on the process steps towards iteratively developing the shared output (hasSharedOutput- i.e. indicates a need to predefine the number of iterations for developing the product by two or more process steps). For example, the code below indicates two process steps, '?taskA' and '?taskB' engaged in the iterative development of the same resource?draft into the property hasSharedOutput:

```
Task (?taskA) ^ hasOutputResource
  (?taskA, ?draft) ^ isInputResourceOf
  (?draft, ?taskB) ^ hasOutputResource
  (?taskB, ?draft2)
-> hasSharedOutput (?taskB, ?taskA)
                                      (2)
```

The third SWRL rule indicates process steps simultaneously calling for the same resources. Since these process steps compete for the same resource; therefore, the resource needs to be prioritised for one of the process steps (symmetric property hasSharedInput):

```
Task (?taskA) ^ hasInputResource
  (?taskA, ?draft) ^ isInputResourceOf
  (?draft, ?taskB) ^ differentFrom
  (?taskA, ?taskB)
-> hasSharedInput (?taskB, ?taskA)
                                      (3)
```

4.3. Dimension 3: interpreting resource dependencies as process transitions

The inferred resource dependencies could be used to construct a process. For example, hasFlowDependency points to the next possible activity that uses the produced resource. At the same time, other properties (hasSharedOutput, hasSharedInput) indicate the need for a decision which can be made manually by a collaboration facilitator or by using Artificial Intelligence. Several possible process steps allow the process owner to decide (e.g. agree, disagree) and optionality for the next step (e.g. sending the tender by post or email). The Collaboration ontology with inferred properties (orange dashed links) is illustrated in Figure 6. Grey-coloured links represent the asserted properties.

For example, we used a formation of a new collaborative tendering process between the actors: *The Lead supplier* and the *Invited partner*. Lead suppliers can form teams on the collaboration platforms (Cisneros-Cabrera et al. 2021; Liu et al. 2022), yet they cannot manually coordinate how to write collaborative tender documentation. The lead supplier receives Calls for tender (as an input resource), prepares a tender draft (output resource), receives input from the partner on the tender, incorporates the input, ensures that the partner agrees with the documentation, and if it is agreed, then submits tender. Finally, the Invited partner provides input to the tender and votes for tender submission. If the Invited partner disagrees with the tendering document, the Lead supplier invites an alternative partner.

In order to arrange these steps into a sequence, all individuals (process steps) were asserted to the collaboration ontology, which infers new semantic relationships (sequences between process steps), Figure 7. The bold yellow links indicate the inferred property ‘hasFlowDependency’, which was identified between ‘t1CreateTenderDraftTask’ and ‘t222MakeInputTask’, based on resource interdependencies, and indicates a potential transition (sequence) between these steps. The purple connection line indicates the instances of a class/subclass, while the yellow dashed line exemplifies the inferred property ‘hasFlowDependency’.

4.4. Dimension 4: BPMN visualisation and execution in a workflow engine

We developed a web tool in JAVA that derives actors, process steps, and the inferred properties from the ontology and, using the algorithm (Figure 5c), visualises the BPMN diagram for a workflow editor, Figure 8. The new inferred properties ‘hasFlowDepenedency’ suggest the potential sequences between the process steps belonging to a *Lead supplier* or *Invited partner;* therefore, all process steps are arranged by their resource dependencies. For example, if there are two ‘hasFlowDependency’ between the process steps, the XOR element is added, inviting the process owner to make a selection.

Unlike conventional static process management approaches, ontology-guided coordination enabled actors,

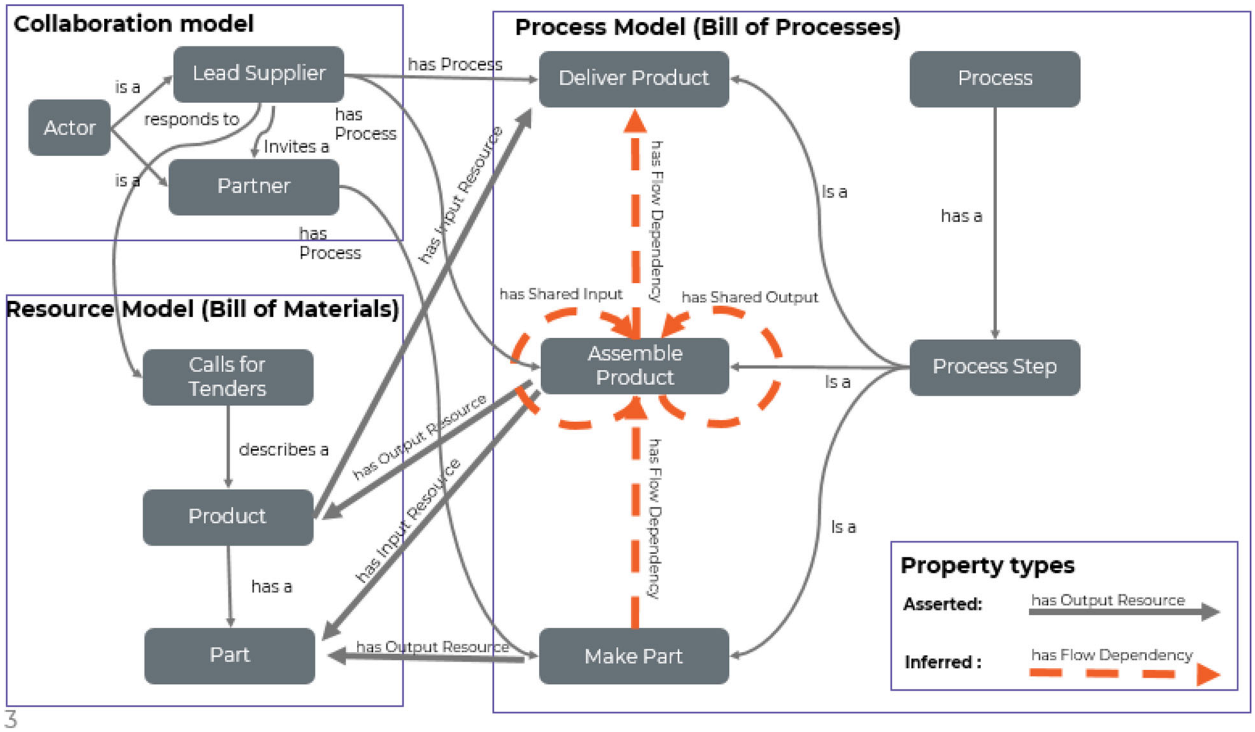


Figure 6. Classes and properties of an experimental ontology: asserted properties hasInputResource/hasOutputResource, inferred property:hasFlowDependency.

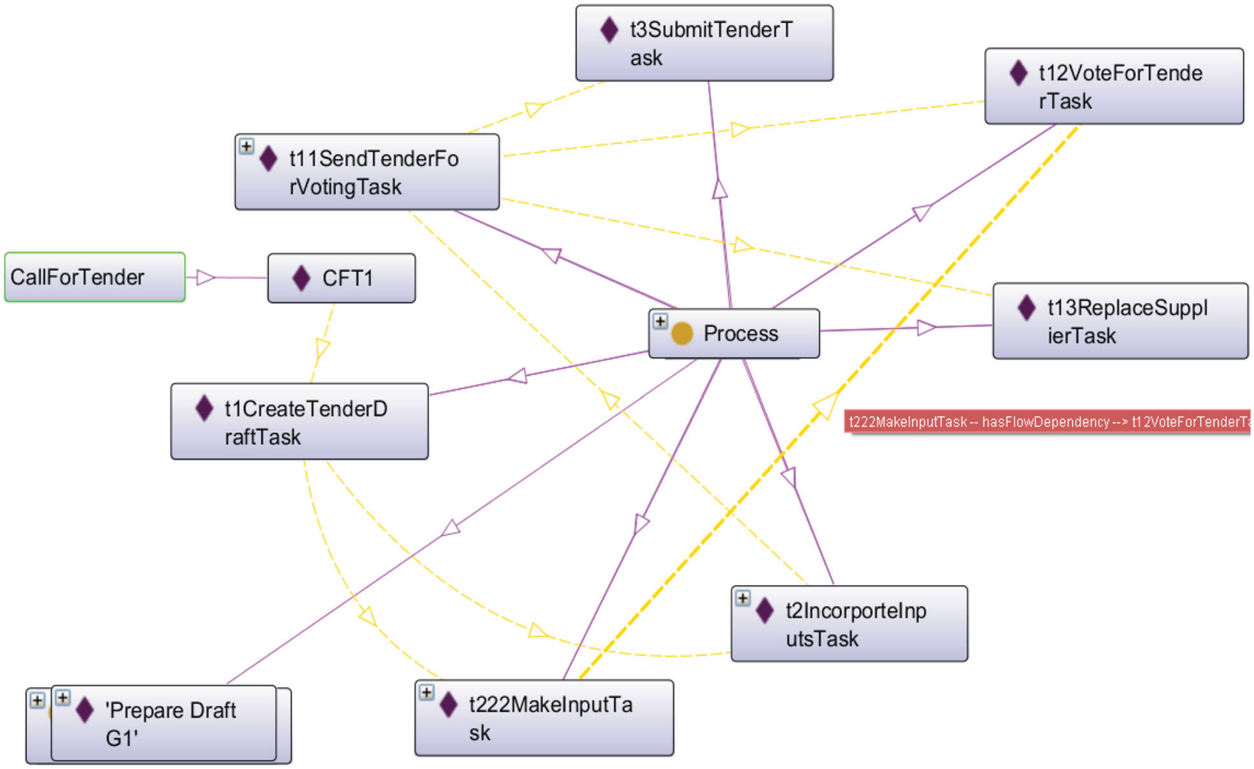


Figure 7. The inferred property 'hasFlowDependency' enables to guide production process formation based on resource dependencies between process steps (excerpt).

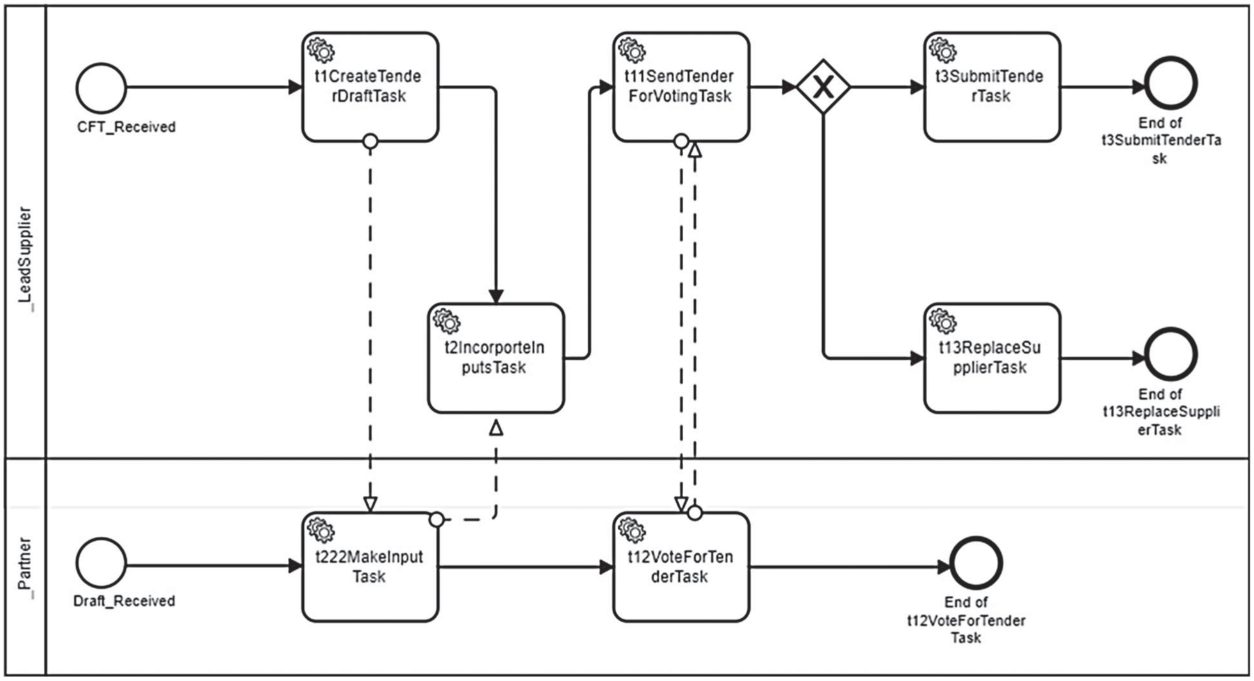


Figure 8. The derived BPMN process of collaborative tendering.[18]

process steps and resource dependencies from the ontology to visualise the process based on the resource demand of each step. In addition, the ontology-guided approach allowed for the process's dynamic formation, which can adjust each time the resource requirements change, thus ensuring flexible process design and coordination of demand-driven collaboration. Finally, the process can be quickly updated for three or more actors or replace steps until the resource requirements are met.

5. Discussion and conclusion

The work reported in this paper advances production research in approaches and tools to facilitate demand-driven collaborations. We propose semantic constructs and reasoning mechanisms to interconnect suppliers and facilitate their collaborative work on tendering documents or awarded manufacturing orders. Furthermore, where the existing pool of suppliers cannot complete the order and external suppliers are needed, our semantic approach can enable demand-driven collaborations with new partners, which is a timely and essential contribution to collaborative industrial engineering.

Ontologies represent a conceptualisation of the real-world products and relationships representing companies' capabilities, CfT requirements, and other concepts essential for forming and maintaining supply-chain collaborations. The ontology-guided approach provides interoperability among SME suppliers from different domains once their processes and resources are included in the shared ontology. It increases SME readiness to collaborate on demand (Perks et al. 2017), thus supporting the work to reduce ripple effects (Dolgui, Ivanov, and Sokolov 2018). We provide the ontological underpinning of a demand-driven collaboration, which allows engaging small and medium-sized enterprises into negotiation whilst forming a flexible collaboration process model. We focus on a new way to build a collaboration process, using input and output resource requirements of each process step, rather than the strict sequential dependency common in workflow and process management tools (Jensen 2013; Van Der Aalst, Van Hee, and van Hee 2004). This paper tackles the research question: '*How to support demand-driven collaboration using semantic technologies for manufacturing process formation and coordination.* In the process of addressing the RQ, we have taken the following steps:

1. Designed the collaboration ontology for forming on-demand collaborations and described its application in natural production settings, where resource dependencies between processes of different levels mediate the formation and coordination of demand-driven collaborations (Kazantsev et al. 2022).
2. Conceptualised and designed the ontology-guided collaboration approach, where three classes arrange process steps: *(MakePart, AssembleProduct* and *DeliverProduct).* The ontology-guided approach supports the agile process formation required in Industry 4.0 supply network scenarios (Ivanov et al. 2020; Moeuf et al. 2018) and supports the creation of collaborative production processes *on the fly* that suppliers could use without any collaboration facilitator (De Vreede and Briggs 2019).
3. Articulated a real-world application of Coordination Theory constructs (Malone and Crowston 1994) in product assembly in a demand-driven collaboration. We implemented the constructs into the ontology for production research, encompassing process steps and properties. It enables forming production processes based on resource dependencies, enabling more flexibility during execution.

To the best of our knowledge, this is the first approach that uses technologies from the Semantic Web, specifically the Web Ontology Language (OWL) and the Semantic Web Rule Language (SWRL), to formalise the collaborative relations between companies and form manufacturing collaboration processes in the context of Industry 4.0 nascent supply chains. One of this work's innovations is using the Semantic Web Rule Language (SWRL) to automate the computation of flow dependencies between processes based on their inputs and outputs. SWRL provides a powerful forward chaining rules engine that allows the definition of logical axioms. These rules are excellent for capturing and enforcing constraints in process management systems. Production and supply chain managers that engaged with our research team appreciated the flexibility and iterative development of a collaboration assembly process.

5.1. Managerial and policy implications

Our ontology constructs a coordinated production process using semantic reasoning, a unique contribution contrasting us from available manufacturing ontologies. At any point in the process, the ontology provides the relevant information either to the orchestrator (e.g. lead supplier) for manual decision-making or to the workflow engine (e.g. digital tool) for automated decision-making based on resource needs. The information from the ontology is critical to enabling a flexible process model for a team of suppliers, which allows replacing partners and rearranging steps until the resource requirements are satisfied. Our approach differs from other process formation methods, which are predefined and unable to support the dynamic formation of teams. In contrast, ontology-guided digital tools can enable a new generation of workflow systems.

The proposed ontology-guided approach allows the reconfiguration of processes based on resource requirements and coordination mechanisms to manage resource interdependencies. Notably, we argue that the derived resource dependencies have an advantage over the static assignment of the following steps, as the coordination via resources enables flexibility and dynamics for process formation and reconfiguration. Furthermore, it enables dynamic connections between process steps and adds options for process designers. Our paper shows a scenario that applies a collaboration ontology with predefined classes, properties, and SWRL rules for facilitating and better structuring demand-driven collaborations. The collaboration ontology has shown practical relevance in underpinning the Industry 4.0 digital collaboration platform DIGICOR by embracing the concepts required for collaborative manufacturing in Industry 4.0, such as *goal*, *value-added activity*, *resource* and *dependency*, ontology-guided semantic reasoning, and decision-making supporting the selection of teams and operationalisation goals. The proposed approach enables flexible collaboration process formation complying with formalised coordination constraints. This provides an essential addition to process management systems research, arguing for using resource-based rather than solely sequence-based dependencies for connecting process steps. The resource-based design features enable flexibility for collaborative process construction. Based on feedback from SME cluster members from our consortium that evaluated our approach, reducing collaboration barriers using semantic technologies will facilitate the setup of new (nascent) collaborations and widen business opportunities.

5.2. Limitations and future work

The limitations of our approach include testing the ontology within the aerospace domain, which implies gaps in validation with other production sectors (e.g. automotive or food manufacturing). Furthermore, we did not deploy the ontology in a large-scale production setting to test scalability and run-time performance. Finally, our work was mainly confined to collaboration process assembly to tackle production goals in the bill of materials of manufacturing tenders.

Future work will explore the potential of ontological relationships and axioms to support collaboration optimisation. For example, automated inference about the notion of 'best teams' based on different strategic priorities, such as fastest delivery, highest customer satisfaction score, and best alignment to sustainability standards. We plan to utilise more of the Semantic Web, especially the SPARQL language, which enables access to large, open, reusable knowledge graphs like dbpedia.org. In addition, it can derive Product and process composition alternatives, exploring the relationships between parts and products and the suitability of prospective suppliers for fulfilling specific tasks the best way. The data properties might be used to calculate the processing time, CO_2 emissions and other metrics valuable for process managers in the production environment. Finally, agile process management, which implies multiple iterations between the actors (in contrast to linear delivery), is another exciting opportunity for ontology-guided process formation and coordination, specifically relevant to distributed large-scale crowdsourcing projects.

Notes

1. https://cordis.europa.eu/project/id/723336 (accessed 27 April 2023)
2. https://cordis.europa.eu/project/id/825075 (accessed 27 April 2023)
3. https://www.hanse-aerospace.net/de/ueber-uns/mitglieder (accessed 27 April 2023)
4. W3C OWL 2.0 Specification https://www.w3.org/TR/owl2-overview/ (accessed 22.12.2022)
5. The implementation of the proposed ontology-guided approach in JAVA is available on GitHub for reproducibility, reuse, and further research https://github.com/QudamahAMBS/coordinationtheory.engine (accessed 03/04/2023)
6. https://ontocommons.eu (accessed 27 April 2023)
7. https://industrialontologies.org (accessed 27 April 2023)
8. https://industrialontologies.org/supply-chain-wg/ (accessed 27 April 2023)
9. EU-funded project DIGICOR https://cordis.europa.eu/project/id/723336, accessed 01.07.2022
10. EU-funded project EFPF https://cordis.europa.eu/project/id/825075, accessed 27.04.2023
11. https://balsamiq.cloud/stg4ncg/p6vz06b (accessed 23.12.2022)
12. https://digitaltwinhub.co.uk/top-level-ontologies/bunge-wand-webber-ontology-r39/ (accessed 24.12.2022)
13. https://ideas.repec.org/a/igg/jswis0/v10y2014i2p7-34.html (accessed 24.12.2022)
14. https://oops.linkeddata.es/ (accessed 24.12.2022)
15. https://webprotege.stanford.edu/#projects/0ef007e9-4229-433d-b6ef-9bb63f9e1a79/edit/Classes (accessed 30.03.2023, registration in Protégé is required)
16. https://cawemo.com/share/8ee81e38-ddc2-4a9c-a824-83819a4ac6a3 (accessed 24.12.2022)
17. '?var' is a convention to indicate variables or missing parts of data, that needs to be found from a tender specification (e.g. bill of materials, bill of processes)
18. This JAVA implementation is available on GitHub for reproducibility, reuse, and further research https://github.com/QudamahAMBS/coordinationtheory.engine (accessed 03/04/2023)

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Data availability statement

Availability of data	Template for data availability statement	Policy
Data available on request due to privacy/ethical restrictions	The data supporting this study's findings are available on request from the corresponding author. The data are not publicly available because they contain information that could compromise the privacy of research participants.	All

Disclosure statement

No potential conflict of interest was reported by the author(s).

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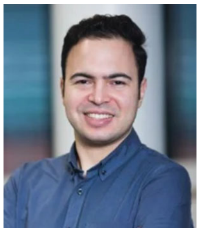

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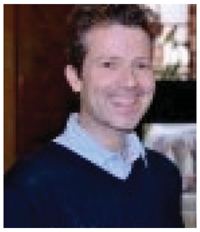

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