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1 Formal Ontologies in Manufacturing

2 Emilio M. Sanfilippo^{ab,*} Yoshinobu Kitamura^c and Robert I.M. Young^d

3 ^a*Le Studium, Loire Valley Institute for Advanced Studies, Orléans & Tours, France*

4 ^b*CESR - Université de Tours, 59, rue Néricault-Destouches, 37020 Tours, France*

5 *E-mail: emilio.sanfilippo@univ-tours.fr*

6 ^c*College of Information Science & Engineering, Ritsumeikan University, Japan*

7 *E-mail: y-kita@fc.ritsumei.ac.jp*

8 ^d*School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, UK*

9 *E-mail: r.i.young@lboro.ac.uk*

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11 Accepted by:

12 Since the early days of ontology engineering, manufacturing is one of the main areas where ontologies
13 have traditionally been applied (Guarino, Borgo, & Masolo, 1997; Uschold & Grüninger, 1996). The
14 interest in ontologies has been motivated, first, by the massive exploitation of computer-based
15 technologies in manufacturing organizations, which need to manage and share data in a robust way, and
16 second, by the need to harmonize different terminologies to facilitate communication. The two
17 motivations are strictly related, since shared terminologies and models are needed to enable computer
18 systems to interact effectively. In addition, in the new landscape of Industry 4.0 (Lu, 2017), guided and
19 informed by big data and machine learning, ontologies find their place to organize the data upon which
20 learning algorithms run.

21 Looking at the literature on manufacturing ontologies, research efforts can be roughly classified
22 in two broad segments: the first one aimed at establishing the conceptual and formal foundations of
23 manufacturing ontologies (Bock, Zha, Suh, & Lee, 2010; Borgo & Leitão, 2007; Grüninger, 2009;
24 Usman et al., 2013), and the second one specifically focused on the use of ontologies in application
25 systems (Colombo, Mosca, & Sartori, 2007; Matsokis & Kiritsis, 2010; Perzylo, Somani, Rickert, &
26 Knoll, 2015; Tessier & Wang, 2013; Terkaj, Pedrielli, & Sacco, 2012). Unfortunately, the two research
27 lines have been co-existing for a long time with only little interaction. Theoretical studies have been left
28 aside and the manufacturing community still lacks robust methodologies for ontology design. At the
29 same time, software applications have not been used as testbed for formal ontologies and it is therefore
30 hard for experts to exploit them. There is few reports on industrial deployment of software applications
31 based on deeply-investigated ontologies (Kitamura, Koji, & Mizoguchi, 2006). It is only recently that
32 some efforts towards the interaction of the two research lines have been carried out. The Industrial
33 Ontologies Foundry (IOF, 2019) is probably the most significant and ambitious example, although it is
34 still too early to say whether it will succeed in supporting the multiple cross-functional interoperability
35 requirements of manufacturing businesses and provide the ontologies, methodologies, and technologies
36 that stakeholders will adopt.

*Corresponding author. E-mail: emiliosanfilippo@gmail.com (permanent address).

1 Independently from the dichotomy between foundational and applied-oriented studies, the
2 ontological representation of manufacturing knowledge has been widely investigated. Traditionally,
3 emphasis has been given to the representation of product knowledge leading to ontologies about
4 features, components, or products' qualities (Fiorentini et al., 2007; Imran & Young, 2015; Vegetti,
5 Leone. & Henning, 2011). In the 90's, some scholars proposed the use of mereologies and mereo-
6 topologies to rigorously model domain-specific spatial relations for product knowledge representation
7 (Borst & Akkermans, 1997; Guarino et al., 1997; Salustri, 1997; Simons & Dement, 1996). This
8 research topic, which was left apart for some years, is getting a momentum nowadays probably under
9 the pressure of advanced technologies that demand robust theories to organize product data (see the
10 work of Aameri, Cheong, & Beck (2019) in this Special Issue for further references). Surprisingly
11 enough, less attention has been given to (the ontological understanding of) manufacturing processes.
12 Despite many papers and the availability of ISO standards like STEP-NC (ISO 10303-238; ISO 2003)
13 and PSL (ISO 18629; Grüniger & Menzel, 2003), the formal and ontological characterization of
14 manufacturing processes, including the resources used, consumed, or transformed during their
15 execution, is a topic for open research. As a matter of fact, disagreements often arise on the very notion
16 of manufacturing process, e.g., whether it covers only the creation (or refinement) of products, or it
17 should be rather broadly understood to cover a larger spectrum of processes occurring in manufacturing
18 organizations. The partial treatment of manufacturing process knowledge has some consequences for
19 the integration of product and process knowledge, for which mature formal and ontological works are
20 scarce. Finally, recall that the wide use of information systems in manufacturing contributed to the
21 development of ontologies in disparate areas including industrial plants design or (re-)configuration
22 (Kádár, Terkaj, & Sacco, 2013), maintenance (see the work of Karray, Ameri, Hodkiewicz, & Louge
23 (2019) in this Special Issue), supply chain data management (Palmer et al., 2016), and product service
24 systems (Shani, Franke, Hribernik, & Thoben, 2017), among others.

25 The requirements of manufacturing industry lead to many open research topics in
26 manufacturing ontology that include (but are not limited to):

- 27
28 • Ontological modeling of manufacturing resources: in the context of Industry 4.0 and under the
29 pressure of continuously evolving manufacturing methods like additive manufacturing,
30 researchers are currently investigating the ontological representation of complex manufacturing
31 resources like Cyber-Physical System (CPS; Horváth & Gerritsen, 2012). These are challenging
32 to be represented and conceptualized not only because of the complex software-hardware
33 structure they have, but also because of their agentic dimension. In order for ontologies to
34 properly characterize CPS, the ontology of "traditional" manufacturing resources needs to be
35 investigated beforehand. For example, it is common in manufacturing to assume an intuitive
36 distinction between resources that execute the desired task such as cutting, polishing, or
37 additive machines, from resources that support the execution of such tasks, e.g., fixtures, jigs,
38 or gauges, among others, and resources that enable the functioning of other resources, e.g.,
39 lubricants, gasoline, or electric energy. The representation of CPS and other emergent Industry
40 4.0 resources would likely benefit of an ontological investigation of these and other similar
41 distinctions.
- 42
43 • Ontological modeling of manufacturing systems: Industry 4.0 envisions the development of
44 fully automated manufacturing environments where inter-connected (agentic) resources
45 mutually interact by exchanging data and taking autonomous decisions on the task they are
46 required to fulfill. These production systems are sometimes called Cyber-Physical Production
47 Systems (CPPS; Monostori, 2014). From a modeling perspective, current research work
48 addresses the use of ontologies to facilitate the exchange of data among the resources used in

1 CPPS (Grangel-González et al., 2016; Garetti, Fumagalli, & Negri, 2015). In our understanding,
2 this focus on applications needs to be complemented with research efforts that address what it
3 means for a CPPS to be a working environment where autonomous and agentive artificial
4 resources interact between them and with humans. Some works towards the analysis of CPPS
5 as socio-technical environments have been already carried out (see the work of Borgo &
6 Sanfilippo (2018) for further references); the results are however still preliminary and further
7 efforts are required. Ontology designers may seek for contributions coming from areas where
8 similar topics have been already investigated, e.g., social ontology, game theory, and multi-
9 agents systems.

- 10
11 • Ontological modeling of manufacturing processes: a robust investigation on the ontological
12 modeling of manufacturing processes is necessary. This includes (at least) 1) defining the very
13 notion of manufacturing process; 2) identifying and distinguishing between different classes of
14 manufacturing processes; 3) characterizing different ways in which objects (e.g., resources)
15 participate in processes; 4) conceptualizing and modeling the relations between processes and
16 plans, as well as between processes, plans, products, and design specifications.
17
- 18 • Ontological modeling of business notions relevant for manufacturing: it is common to describe
19 the manufacturing world by emphasizing its business dimension. From this perspective,
20 products are items that are sold for the economical benefit of companies (see the paper of Otte
21 et al. (2019) in this Special Issue), processes are executed according to business policies and
22 regulations, resources are owned by organizations, and manufacturing organizations themselves
23 interact according to the business goals they are meant to achieve. Business-related notions
24 have been left apart from manufacturing ontologies and their modeling is therefore needed.
25
- 26 • Adoption of foundational ontologies for manufacturing: the interest of the engineering
27 community for foundational ontologies like Basic Formal Ontology (BFO; Arp, Smith, & Spear,
28 2015), Unified Foundational Ontology (UFO; Guizzardi, Wagner, Almeida, & Guizzardi, 2015),
29 or Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE; Masolo et al.,
30 2003), among others, is growing because of the need for well-defined and principled
31 frameworks for knowledge and data management. By their very nature, foundational ontologies
32 are complex systems whose technicalities are often hard to grasp by the average domain expert
33 who likely lacks a background in formal logic or philosophical ontology (Stevens, Lord,
34 Malone, & Matentzoglou, 2019). In addition, only few works have attempted to measure the
35 effectiveness of different foundational ontologies for practical needs such as data modeling or
36 information systems interoperability (Keet, 2011; Stevens et al., 2019). A consequence is that
37 the choice of adopting a certain foundational ontology is commonly motivated by concerns
38 others than its conceptual or logical robustness. Efforts are required to avoid this and to help
39 domain experts in selecting and properly using the foundational ontology that is best suited for
40 their purposes. First, from a bottom-up perspective, robust case studies are needed to
41 understand how efficient foundational ontologies are in satisfying manufacturing experts'
42 requirements. Second, from a top-down perspective, ontologists need to define methodologies
43 to support domain experts modeling tasks but also to help them in understanding the technical
44 aspects of foundational ontologies. Third, different academic “schools of thoughts” should
45 collaborate in transferring to stakeholders their knowledge and experience by promoting the
46 methodologies they share rather than by competing for (possible) market benefits.
47

- 1 • Modeling languages: most of the ontologies currently available for the manufacturing domain
2 are formalized in Semantic Web languages, the Web Ontology Language (OWL) foremost
3 (Negri, Fumagalli, Garetti, & Tanca, 2016). This allows to rely on disparate technologies
4 nowadays available (e.g., to store, query, or visualize data), as well as to reason over knowledge
5 and data in a tractable manner. Notoriously, however, the expressivity of Semantic Web
6 languages is limited and modelers often need to come with ad hoc workarounds, e.g., when
7 ternary relations are needed. Alternative approaches have been explored within the
8 manufacturing community but they have received only scarce attention (Grüninger & Katsumi,
9 2012; Imran & Young, 2015). We think that the research community would benefit from the
10 investigation of modeling frameworks and languages other than Semantic Web languages to
11 face the challenges of ontology modeling in manufacturing. Some inputs may come from the
12 use of the Distributed Modeling Language (DOL; Mossakowski, Codescu, Neuhaus, & Kutz,
13 2015), logic programming approaches based on, e.g., Prolog (Lloyd, 1993) or Answer Set
14 Programming (ASP; Lifschitz, 2008), or Common Logic based knowledge management
15 systems (Grüninger & Katsumi, 2012; Imran & Young, 2015).
16

17 This list is not meant to exhaust the range of research topics to be addressed in manufacturing
18 ontology. It is indeed likely the case that the emergence of new conceptual paradigms about the
19 industrial world and the development of advanced computer-based technologies will enrich the research
20 agenda. However, fundamental questions about the nature of the basic entities found in manufacturing
21 ontologies (e.g., products, resources, processes, production systems, etc.) cannot and should not be
22 dismissed. In addition, there are many practical issues that constrain manufacturing business
23 competitiveness that can benefit from ontological solutions. Key amongst these are (i) interoperability
24 across multi-domain, multi-business and multi-systems, (ii) software environments that support the
25 rapid dynamic change requirements of businesses, (iii) minimizing the cost of developing business
26 specific knowledge environments through the re-use of standardized ontologies, (iv) manufacturing
27 knowledge maintenance methods as businesses advance their manufacturing understanding.
28

29 This Special Issue on Applied Ontology with title *Formal Ontologies in Manufacturing* has
30 been thought to address foundational issues in manufacturing ontology but also to provide technical
31 insights about ontology-based applications. Many journals in the manufacturing domain recurrently
32 publish papers on ontologies, and the Semantic Web journal and the Journal of Engineering Design are
33 about to publish special issues about ontologies in and for industry and design. On our side, the choice
34 of editing this Special Issue on Applied Ontology depended on at least three reasons. First, Applied
35 Ontology has historically adopted a strongly interdisciplinary approach, which is fundamental in our
36 understanding to characterize a complex domain like manufacturing. Second, the journal emphasizes
37 the need for principled approaches to guide the development of ontologies. Third, Applied Ontology
38 welcomes papers where ontologies are represented in expressive formal languages. Our aim was
39 therefore to collect research papers presenting challenging modeling problems concerning knowledge
40 representation in manufacturing and providing mature ontological analysis and formal models.
41

42 The papers submitted for the Special Issue, out of which three are hereby published, spanned
43 across the entire manufacturing domain, from formal theories to represent parthood relations for
44 assembly, to manufacturing types modeling, agent-based systems for Industry 4.0, core manufacturing
45 ontologies, the modeling of product variability, etc.

46 Aameri et al. (2019) present the Assembly Ontology for generative design: automatic
47 generation of feasible design solutions based on given design goals and constraints. The ontology
48 specifies connection, parthood, and shapes in mechanical assemblies for logical expressions of such
49 qualitative constraints. The ontology extends the theory of Ground Mereotopology (MT) and combines

1 it with a qualitative shape ontology based on the Hilbert's axiomatic theory of geometry. The paper
2 describes its formal axiomatization and demonstrates its application in axiomatic representation of
3 suspension systems. With respect to the research challenges mentioned above, this paper contributes to
4 the formal treatment of engineering knowledge in languages other than OWL. Also, it contributes to the
5 exploitation of theories of formal ontology like MT for engineering modeling purposes. In our
6 understanding, the paper presents a promising research contribution to support both the representation
7 of and reasoning over assembly structures in a principled way.

8 Karray et al. (2019) introduces the ROMAIN ontology for knowledge representation and data
9 modeling in the manufacturing maintenance domain. The ontology builds on the BFO in order to reuse
10 its upper-level modeling elements and enable data and applications interoperability with BFO-aligned
11 ontologies. According to the authors, BFO was selected as reference upper-level because its successful
12 use for interoperability has been already extensively documented. To validate ROMAIN against experts'
13 knowledge, the paper presents a case study where the ontology is used to organize and retrieve
14 maintenance data. From a more general perspective, this contribution is a step forward in the
15 ontological modeling of maintenance knowledge, which also addresses challenging issues that
16 researchers will need to face to foster the adoption of ontologies for maintenance knowledge and/or data
17 management. In addition, by relying on the BFO, the paper shows the willingness of the engineering
18 community not only in using upper-level ontologies to facilitate ontology development or
19 data/applications interoperability but also in analyzing domain knowledge with respect to formal
20 ontology theories (e.g., theory of objects, qualities, processes, dependence, mereology, etc.).

21 Otte et al. (2019) present a suite of modular ontologies called the Product Life Cycle (PLC)
22 ontologies for data system interoperability in the manufacturing industry. The ontology relies on both
23 the BFO and the suite of mid-level ontologies called the Common Core Ontology (CCO). The paper
24 discusses definitions of fundamental concepts in the product life cycle such as 'product', 'commodities',
25 'is input of', and 'provision of a service' based on the definitions in BFO. With respect to general
26 research challenges, the paper is a contribution towards the definition of a core ontology for
27 manufacturing based on a foundational ontology. Also, it presents an analysis of domain notions with
28 respect to both engineering and economics, which – as previously said – is relevant to characterize the
29 business dimension of manufacturing knowledge and data.

30
31 We hope that this Special Issue will contribute to stimulate the research community in digging into the
32 ontological modeling of manufacturing knowledge with an open-minded attitude from both ontologists
33 towards manufacturing and manufacturing experts towards formal ontology.

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