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## Editorial

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# Formal ontologies in manufacturing

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

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

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

24 The requirements of manufacturing industry lead to many open research topics in manufacturing on- 24  
25 tology that include (but are not limited to): 25  
26

- 27 • Ontological modeling of manufacturing resources: in the context of Industry 4.0 and under the 27  
28 pressure of continuously evolving manufacturing methods like additive manufacturing, researchers 28  
29 are currently investigating the ontological representation of complex manufacturing resources like 29  
30 Cyber-Physical System (CPS; Horváth and Gerritsen, 2012). These are challenging to be repre- 30  
31 sented and conceptualized not only because of the complex software-hardware structure they have, 31  
32 but also because of their agentive dimension. In order for ontologies to properly characterize CPS, 32  
33 the ontology of "traditional" manufacturing resources needs to be investigated beforehand. For ex- 33  
34 ample, it is common in manufacturing to assume an intuitive distinction between resources that 34  
35 execute the desired task such as cutting, polishing, or additive machines, from resources that sup- 35  
36 port the execution of such tasks, e.g., fixtures, jigs, or gauges, among others, and resources that 36  
37 enable the functioning of other resources, e.g., lubricants, gasoline, or electric energy. The repre- 37  
38 sentation of CPS and other emergent Industry 4.0 resources would likely benefit of an ontological 38  
39 investigation of these and other similar distinctions. 39
- 40 • Ontological modeling of manufacturing systems: Industry 4.0 envisions the development of fully 40  
41 automated manufacturing environments where inter-connected (agentive) resources mutually in- 41  
42 teract by exchanging data and taking autonomous decisions on the task they are required to ful- 42  
43 fill. These production systems are sometimes called Cyber-Physical Production Systems (CPPS; 43  
44 Monostori, 2014). From a modeling perspective, current research work addresses the use of ontolo- 44  
45 gies to facilitate the exchange of data among the resources used in CPPS (Grangel-González et al., 45  
46 2017). 46

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

- Ontological modeling of manufacturing processes: a robust investigation on the ontological modeling of manufacturing processes is necessary. This includes (at least) 1) defining the very notion of manufacturing process; 2) identifying and distinguishing between different classes of manufacturing processes; 3) characterizing different ways in which objects (e.g., resources) participate in processes; 4) conceptualizing and modeling the relations between processes and plans, as well as between processes, plans, products, and design specifications.
- Ontological modeling of business notions relevant for manufacturing: it is common to describe the manufacturing world by emphasizing its business dimension. From this perspective, products are items that are sold for the economical benefit of companies (see the paper of Otte et al., 2019 in this Special Issue), processes are executed according to business policies and regulations, resources are owned by organizations, and manufacturing organizations themselves interact according to the business goals they are meant to achieve. Business-related notions have been left apart from manufacturing ontologies and their modeling is therefore needed.
- Adoption of foundational ontologies for manufacturing: the interest of the engineering community for foundational ontologies like Basic Formal Ontology (BFO; Arp et al., 2015), Unified Foundational Ontology (UFO; Guizzardi et al., 2015), or Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE; Masolo et al., 2003), among others, is growing because of the need for well-defined and principled frameworks for knowledge and data management. By their very nature, foundational ontologies are complex systems whose technicalities are often hard to grasp by the average domain expert who likely lacks a background in formal logic or philosophical ontology (Stevens et al., 2019). In addition, only few works have attempted to measure the effectiveness of different foundational ontologies for practical needs such as data modeling or information systems interoperability (Keet, 2011; Stevens et al., 2019). A consequence is that the choice of adopting a certain foundational ontology is commonly motivated by concerns others than its conceptual or logical robustness. Efforts are required to avoid this and to help domain experts in selecting and properly using the foundational ontology that is best suited for their purposes. First, from a bottom-up perspective, robust case studies are needed to understand how efficient foundational ontologies are in satisfying manufacturing experts' requirements. Second, from a top-down perspective, ontologists need to define methodologies to support domain experts modeling tasks but also to help them in understanding the technical aspects of foundational ontologies. Third, different academic "schools of thoughts" should collaborate in transferring to stakeholders their knowledge and experience by promoting the methodologies they share rather than by competing for (possible) market benefits.
- Modeling languages: most of the ontologies currently available for the manufacturing domain are formalized in Semantic Web languages, the Web Ontology Language (OWL) foremost (Negri et al., 2016). This allows to rely on disparate technologies nowadays available (e.g., to store, query, or visualize data), as well as to reason over knowledge and data in a tractable manner. Notoriously,

1 however, the expressivity of Semantic Web languages is limited and modelers often need to come 1  
2 with ad hoc workarounds, e.g., when ternary relations are needed. Alternative approaches have 2  
3 been explored within the manufacturing community but they have received only scarce attention 3  
4 (Grüninger and Katsumi, 2012; Imran and Young, 2015). We think that the research community 4  
5 would benefit from the investigation of modeling frameworks and languages other than Semantic 5  
6 Web languages to face the challenges of ontology modeling in manufacturing. Some inputs may 6  
7 come from the use of the Distributed Modeling Language (DOL; Mossakowski et al., 2015), logic 7  
8 programming approaches based on, e.g., Prolog (Lloyd, 1993) or Answer Set Programming (ASP; 8  
9 Lifschitz, 2008), or Common Logic based knowledge management systems (Grüninger and Kat- 9  
10 sumi, 2012; Imran and Young, 2015).

11 This list is not meant to exhaust the range of research topics to be addressed in manufacturing ontol- 11  
12 ogy. It is indeed likely the case that the emergence of new conceptual paradigms about the industrial 12  
13 world and the development of advanced computer-based technologies will enrich the research agenda. 13  
14 However, fundamental questions about the nature of the basic entities found in manufacturing ontolo- 14  
15 gies (e.g., products, resources, processes, production systems, etc.) cannot and should not be dismissed. 15  
16 In addition, there are many practical issues that constrain manufacturing business competitiveness that 16  
17 can benefit from ontological solutions. Key amongst these are (i) interoperability across multi-domain, 17  
18 multi-business and multi-systems, (ii) software environments that support the rapid dynamic change 18  
19 requirements of businesses, (iii) minimizing the cost of developing business specific knowledge 19  
20 environments through the re-use of standardized ontologies, (iv) manufacturing knowledge maintenance 20  
21 methods as businesses advance their manufacturing understanding. 21

22 This Special Issue on Applied Ontology with title *Formal Ontologies in Manufacturing* has been 22  
23 thought to address foundational issues in manufacturing ontology but also to provide technical insights 23  
24 about ontology-based applications. Many journals in the manufacturing domain recurrently publish 24  
25 papers on ontologies, and the Semantic Web journal and the Journal of Engineering Design are about to 25  
26 publish special issues about ontologies in and for industry and design. On our side, the choice of edit- 26  
27 ing this Special Issue on Applied Ontology depended on at least three reasons. First, Applied Ontology 27  
28 has historically adopted a strongly interdisciplinary approach, which is fundamental in our understand- 28  
29 ing to characterize a complex domain like manufacturing. Second, the journal emphasizes the need 29  
30 for principled approaches to guide the development of ontologies. Third, Applied Ontology welcomes 30  
31 papers where ontologies are represented in expressive formal languages. Our aim was therefore to col- 31  
32 lect research papers presenting challenging modeling problems concerning knowledge representation in 32  
33 manufacturing and providing mature ontological analysis and formal models. 33

34 The papers submitted for the Special Issue, out of which three are hereby published, spanned across 34  
35 the entire manufacturing domain, from formal theories to represent parthood relations for assembly, to 35  
36 manufacturing types modeling, agent-based systems for Industry 4.0, core manufacturing ontologies, the 36  
37 modeling of product variability, etc. 37

38 Aameri et al. (2019) present the Assembly Ontology for generative design: automatic generation of 38  
39 feasible design solutions based on given design goals and constraints. The ontology specifies connection, 39  
40 parthood, and shapes in mechanical assemblies for logical expressions of such qualitative constraints. 40  
41 The ontology extends the theory of Ground Mereotopology (MT) and combines it with a qualitative 41  
42 shape ontology based on the Hilbert's axiomatic theory of geometry. The paper describes its formal 42  
43 axiomatization and demonstrates its application in axiomatic representation of suspension systems. With 43  
44 respect to the research challenges mentioned above, this paper contributes to the formal treatment of 44  
45 engineering knowledge in languages other than OWL. Also, it contributes to the exploitation of theories 45  
46

1 of formal ontology like MT for engineering modeling purposes. In our understanding, the paper presents  
2 a promising research contribution to support both the representation of and reasoning over assembly  
3 structures in a principled way.

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

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

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

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