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Zero Defect Manufacturing ontology: A preliminary version based on standardized terms

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ABSTRACT

The global transition from traditional manufacturing systems to Industry 4.0 compatible systems has already begun. Therefore, the digitization of the manufacturing systems across the globe is increasing with exponential growth which implies a significant increase in the volume and variety of the generated data. Industry 4.0 technologies are mostly data driven and therefore, manufacturers need to be equipped with the appropriate tools and skill sets to extract useful knowledge and insights from the plethora of data continually collected form shop floors. Furthermore, quality assurance is a key domain in manufacturing that uses almost all the industry 4.0 technologies and has great impact on the sustainability of a manufacturing systems. The latest approach to higher quality and manufacturing sustainability is named Zero Defect Manufacturing (ZDM). ZDM interest has spiked the last three years illustrating the need for an alternative quality assurance approach from the traditional such as Six Sigma and Lean manufacturing. Therefore, the goal of this paper is to create a ZDM ontology that can semantically align multiple software systems that interact in a ZDM ecosystem. The development of the proposed ZDM ontology was performed using the principles introduced by Industrial Ontology Foundry (IOF) and with the use of Basic formal ontology (BFO) as an upper level ontology. The proposed ontology was utilized in the Prediction Optimization Designer tool developed, to assist developers to create new projects reusing existing resources, or to respond to a specific challenge. The use case validation results show that the combination of Natural Language Processing (NLP) using Sentence-BERT and ontology-based search methods rooted in the ZDM ontology is a promising strategy to implement effective search engines for applications in the ZDM domain.

1. Introduction

Contemporary manufacturing domain is undergoing a vast change brought about by the Industry 4.0 paradigm. The global transition from traditional manufacturing systems to Industry 4.0 compatible systems has already begun. Therefore, the digitization of the manufacturing systems across the globe is increasing with exponential growth which implies a significant increase in the volume and variety of the generated data (da Xu et al., 2018). Industry 4.0 technologies are mostly data driven and therefore, manufacturers need to be equipped with the appropriate tools and skill sets to extract useful knowledge and insights from the plethora of data continually collected form shop floors. Some of the most data intensive Industry 4.0 technologies are artificial intelligence, machine learning, internet of things, virtual reality, and digital twins (Rosin et al., 2019; Psarommatis and May, 2022). The digital transformation has reshaped the entire manufacturing domain, from the way products are manufactured distributed or designed (Mittal et al., 2019). Therefore, for the successful implementation of Industry 4.0 technologies, data need to be collected, processed, analyzed, communicated, and stored as efficiently as possible. Due to the increase in the complexity of modern manufacturing systems and the diversity and heterogeneity of different industrial software systems that generate and consume data, more advanced techniques for data harmonization, integration, and synthesis are needed. The lack of data semantics is a

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major shortcoming of traditional data modelling methods. Data integrity and interoperability is a major requirement for successful realization of the vision of Industry 4.0 and beyond (Ameri et al., 2021). Using various types of semantic models, including ontologies, to enrich data with context and add meaning to the data is imperative for interoperability and efficient knowledge extraction and reuse.

The application domain that this paper focuses on is the quality assurance domain. It is a key domain that uses almost all the industry 4.0 technologies and has great impact on the sustainability of a manufacturing systems (Psarommatis et al., 2022a). In a manufacturing business, poor product quality can have significant impact on several levels such as direct and indirect financial losses, increased environmental impact, and in general increased waste of resources. So, if manufacturing companies want to maintain or enhance their operational, financial, and environmental performance, quality management is essential (Kumar et al., 2018; Psarommatis et al., 2020a). Additionally, poor quality can have societal effects also, by damaging the company's reputation through its inferior products and the dissatisfaction of customers (Jun et al., 2020). To develop high-quality products with minimum performance loss, manufacturers must employ at least one quality improvement (QI) technique (Psarommatis et al., 2020a). There is still more to be done even though firms have been using traditional QI techniques like six sigma, lean manufacturing, theory of constraints, and comprehensive quality management for more than three decades.

The latest approach to higher quality and manufacturing sustainability is named Zero Defect Manufacturing (ZDM) (Psarommatis et al., 2020b, 2021a). ZDM interest has spiked the last three years illustrating the need for an alternative quality assurance approach from the traditional such as Six Sigma and Lean manufacturing (Psarommatis et al., 2020a). ZDM aims to completely eradicate defects through defect repair and prevention as well as the identification and adjustment of defected goods and process parameters (Powell et al., 2022). With the advent of digitization and Industry 4.0, the technology-intensive idea of ZDM started to acquire more momentum on the quality management agenda, holding the promise of a brand-new generation of digitally improved quality management (Psarommatis et al., 2020b, 2021a; Powell et al., 2022). Information from various levels of the plant should be accessible to create integrated control solutions, particularly when it comes to production quality. Since modern ZDM solutions go beyond conventional data mining methodologies, manufacturing execution system (MES) has become relevant as a central software module for their application, but they still need a standardized strategy for it (Magnanini et al., 2020).

ZDM aims to improve the sustainability of industrial systems and decrease any form of waste (Psarommatis et al., 2021a). Four ZDM strategies—detect, predict, prevent, and repair—are used to accomplish this, which are used in pairs. According to Psarommatis et al., 2020 (Psarommatis et al., 2020b), there are three possible pair strategies: repairing an existing defect (detect-repair), attempting to prevent new ones (detect-prevent), and leveraging data from identified anomalies to predict when defects will emerge soon and prevent them (predict-prevent). A defect could at the product or process level. When a quality problem is found at the process level, maintenance is the answer. For instance, when an equipment failure is predicted, predictive maintenance is necessary to keep KPIs at the target levels (Psarommatis et al., 2021b). The design of the product and the production method both play a big part in achieving ZDM. There are very few studies on how to design a manufacturing system for achieving ZDM. Psarommatis 2021 offered an approach using a digital twin for correctly designing a manufacturing system for using the four ZDM strategies and with a goal to accomplish ZDM (Psarommatis, 2021). The semantic modeling of data and in general information models have a crucial impact on the effectiveness and capacities of data driven and in general Industry 4.0 technologies (Ameri et al., 2021; Grevenitis et al., 2019; Psarommatis et al., 2022b; Mourtzis et al., 2021). Currently, the first standard on ZDM is available by CEN/CENELEC and DIN and therefore the is a concrete definition of ZDM, CWA 17918 (CEN/CENELEC CWA, 2022). Below the definition of ZDM is presented for the ease of the readers:

> "*ZDM is a holistic approach for ensuring both process and product quality by reducing defects through corrective, preventive, and predictive techniques, using mainly data-driven technologies and guaranteeing that no defective products leave the production site and reach the customer, aiming at higher manufacturing sustainability*." (Psarommatis et al., 2021a)

ZDM is a critical approach that heavily is depending on data and collaboration of multiverse software applications which can significantly benefit from ontologies and data semantics (Ameri et al., 2021; Grevenitis et al., 2019; Hildebrand et al., 2019; Cameron et al., 2022). Currently, there is no ontology that covers the ZDM domain. Therefore, the goal and novelty of the research reported in this paper is to create a ZDM ontology that can semantically align multiple software systems that interact in a ZDM ecosystem. The development of the proposed ZDM ontology was performed using the principles introduced by Industrial Ontology Foundry (IOF) and with the use of Basic formal ontology (BFO) as an upper-level ontology. The developed ontology was validated based on a real industrial case.

The structure of the paper is as follows, Section 2 presents the literature review performed for demonstrating the contemporary issues regarding the systems interoperability and the role of ontologies to this issue (Section 2.1), Section 2.2 presents the Basic Formal Ontology (BFO) and its characteristics and purpose. Sections 2.3 and 2.4 are devoted for presenting the Industrial ontology foundry (IOF) initiative and IOF methodology. Section 2.5 discuss some existing ontologies related to ZDM. Section 3 presents the developed ZDM ontology, and the steps followed. More specifically, Section 3.1 presents the terminology used and Section 3.2 the ontology itself. To demonstrate the used and need of the ZDM ontology an industrial use case was used, and therefore in Section 4 the industrial use case is presented. Finally, Section 5 contains the conclusions from the current paper.

2. State of the art

2.1. *Interoperability challenge and role of ontologies*

Lack of syntactic and semantic interoperability among heterogenous systems and organizations is a major barrier to efficient collaboration and information exchange (Chen and Daclin, 2010). *Interoperability* can be defined as the ability of two or more heterogeneous, yet relevant, systems to communicate, correctly interpret, and act on information meaningfully and accurately with minimal effort (Chapurlat and Daclin, 2012a). Governments and industry often tackle the interoperability challenge through the vehicle of standards. Unfortunately, the traditional standards-based approaches for achieving interoperability are expensive and slow (Cargill, 2011). Additionally, standards are brittle since they are often developed based on singular viewpoints of the world, and therefore, they are valid only in specific domains and contexts (Fischer et al., 2015).

Ontologies provide an opportunity to resolve problems of both syntactic and semantic interoperability (Blobel et al., 2009; Grevenitis et al., 2019; Bodenreider, 2008) by providing a systematically curated body of vocabulary and formal definition to support consistent exchange of data among humans and machines (da Xu et al., 2018; Chapurlat and Daclin, 2012b). Another advantage of ontologies is using logic-based models which make ontological entities unambiguous and readable both for humans and machines. In contrast to standards that follow a lengthy and often complex development and approval process, ontologies can be developed and tested in a more agile manner and can provide cross-domain viewpoints (Hagedorn et al., 2019; Smith and Ceusters, 2010). Additionally, ontologies can be implemented incrementally to realize the benefits from enhanced interoperability even at very early stages of ontology development process (Stenzhorn et al., 2008).

Common, consensus-based ontologies have proven themselves in various domains, including the domains of biomedical and biology and financial business applications (Bennett, 2013), as effective solutions for achieving interoperability. In the industrial domain, in contrast, the use of ontologies has not lived up to initial expectations associated for example with ontoSTEP (Barbau et al., 2012) and similar initiatives from the early 2000 s

One reason for lack of widespread adoption of ontologies in manufacturing is that each community (enterprise, industry sector, academic research project) assumes that the proper strategy to solve the problem of semantic interoperability is to create an ad hoc ontology of their own needs. This fragmented approach to ontology development has created an additional problem of *ontology silos* on top the existing problem of *data siloes* (Simon et al., ,). Attempts for connecting siloed ontologies through ontology mapping have not been very successful since mappings are often brittle and quickly render invalid because the existing mappings for a given ontology are often ignored during ontology extension and maintenance process (Song et al., 2013). Ontology adaptation in industry thus remains primarily at the level of research and exploration rather than large-scale industrial applications, perhaps with the exception of Oil and Gas industry in Norway (Aseeri and Wongthongtham, 2011). Industrial companies have predominantly remained hesitant to use formal ontologies due to continued lack of understanding about the utilities of ontologies and the immaturity of the field in industry (Fraga et al., 2020). Industrial Ontology Foundry (IOF) is an initiative that has been launched with the objective of promoting formal ontologies and increasing their adoption in industrial applications. This work follows the development principles of IOF.

A multi-layer and hybrid (top-down and bottom-up) approach is used in developing the ZDM ontology in a sense that a top-level ontology plus some modules of a few mid-level ontologies are used as the starting point for ontology development process. Also, detailed use cases are adopted to define the requirement of the ontology based on specific domain-level objectives and competency questions. BFO is used as the top-level ontology. Mid-level ontological constructs are imported form IOF ontologies, Common Core (CCO) ontologies, and Information Artifact Ontology (IAO).

Numerous projects have released frameworks and rules for how they understand "smart manufacturing" (Bader et al., 2019; Weyrich and Ebert, 2016). An asset is defined as an object that has value to an organization, and the German initiative "Plattform Industrie 4.0" developed the Reference Architecture Model Industrie 4.0 (RAMI4.0) with the aim of sufficiently defining the description of an asset or a combination of assets over the entire product life cycle, DIN SPEC 91345 2016 (Das, 2022). The complicated correlations of an asset are organized according to a layer model called RAMI4.0, which ensures that at any stage in the asset's life cycle, all pertinent information is available. Furthermore, Industrial Internet Reference Architecture (IIRA), which serves as an architectural model and guidance for the creation, documentation, communication, and deployment of distinctive Industrial Internet of Things (IIoT) systems, promotes system interoperability between various industrial sectors by fostering a common understanding through data modelling and semantics (Göppert et al., 2021).

2.2. Basic formal ontology

Top-level ontologies (TLO) (foundational ontologies or upper ontologies) provide abstract and philosophical formalization of the entities that needed to represent a domain. The entities represented in TLOs are intended to be domain-neutral and generic with the same interpretation across all domains. Several studies have shown that using TLOs can improve the efficiency of the ontology-development process as well as the quality of the resulting ontology (Keet, 2011). When a TLO is used in developing an ontology, one does not need to "reinvent the wheel" by defining basic entities such as process, object, or temporal regions that are often used in representing any domain (Keet, 2022). Another advantage of using a TLO is that it improves the overall quality of the ontology by enforcing a multi-tiered, hierarchical architecture and a principled ontology development procedure. TLOs also facilitate interoperability among the ontologies that use the same foundational ontology. Upper ontologies provide a prominent role in integrating heterogenous knowledge models. They can serve as an interlingua for communication among heterogenous software agents with varying local viewpoints and perspectives (Mascardi et al., 2022). Some of the notable upper level ontologies include Basic Formal Ontology (BFO) (Guizzardi and Wagner, 2022), Domain Ontology for Linguistic and Cognitive Engineering (DOLCE) (Masolo et al., ,), Unified Foundational Ontology (UFO) (Guizzardi and Wagner, 2022), and Suggested Upper Merged Ontology (SUMO) (Niles and Pease, 2001).

In this work, BFO is used as the upper-level ontology. BFO has been used successfully in the biological domain for integrating disparate ontologies or developing interoperable ontologies (Hoehndorf et al., 2015). Also, recently it has been adopted as an ISO standard for top-level ontologies and it is freely available to those working on standards and ontologies (ISO, 2022). There are multiple reasons that make BFO a suitable TLO for most applications. Firstly, BFO has a fairly large user base and it is widely used in a variety of ontologies from various domains. Secondly, BFO is relatively small and therefore, easy to use and easy to learn. Additionally, BFO is very well-documented and there are multiple tutorials, guidelines, and web forums for using BFO in ontological projects.

One of the major distinctive features of BFO is that it adopts a *realist approach* (as opposed to a conceptual approach) and represents different types of entities that exist in the world and relations between them. The notion of *ontological realism* refers to the idea that an ontology should be analogous not to a data model, but rather to a reality model. Accordingly, the asserted classes of BFO and its extensions are intended to represent reality based on our best scientific understanding of world. Studies have found that adopting realist approach would enhance the utility of the ontology with respect to interoperability, scalability, reusability, and clarity in various domains including systems engineering (Merrell et al., 2021). At the same time, with a realist bias, the representation of cognitive entities including ad hoc conceptualizations (such as Key Performance Indicators), mathematical constructs, and agentive perspectives and intentions becomes challenging and workarounds would be needed.

2.3. Industrial Ontologies Foundry (IOF)

The IOF is an international community of academia, industry, and research institutes that was formed with the vision of increasing the adoption of ontologies in the manufacturing sector (Smith et al., 2019). Its aims are to develop and disseminate a set of coherent reference ontologies and promote their adoption as a means of advancing software and data interoperability in the manufacturing sector. Its scope is the entire domain of the manufacturing industry. Once fully developed, IOF will provide an open-source platform for developing, validating, aligning, sharing, and curating industrial ontologies. IOF is committed to meet the needs of industrial stakeholders by providing a reliable turnkey solution process for integrating ontologies in their businesses. The IOF provides a set of open and principles-based ontologies, from which other domain or enterprise-dependent or application ontologies can be derived in a modular fashion and providing principles and best practices by which quality ontologies can be developed that will support interoperability for industrial domains. IOF ontologies remain 'generic' (i.e., non-proprietary, non-implementation specific) so they can be reused in any number of industrial domains, standard bodies, or enterprises.

The technical goals of IOF include (Technical Principles, 2022):

- Create open, principles-based ontologies from which other domain-dependent or application-specific ontologies can be derived in a modular fashion.

- Ensure that IOF ontologies are non-proprietary and non-implementation-specific, so they can be reused in different industrial subdomains and standard bodies.
- Provide principles and best practices by which quality ontologies will support interoperability
- Institute a governance mechanism to maintain and promulgate the goals and principles.
- Provide an organizational framework and governance processes that ensure conformance to IOF principles and best practices.

The main focus of IOF is on developing domain-specific reference ontologies that can be further specialized to create application ontologies for various use cases. A Reference Ontology represents the theories and the general knowledge of the domain independent of particular applications. Domain-specific Reference Ontologies (DSRO) are reused across multiple applications in the domain. IOF ontologies are aligned with BFO as the Top-Level Ontology.

Currently there are five active working groups (WGs) in IOF. Four of them address different subdomains of manufacturing including Supply Chain, Production Planning and Scheduling, Maintenance, Product-Service Systems, Systems Engineering, and MTConnect. The last working group, namely the Core WG, serves as the glue by providing a common ontology and ensuring consistency across other working groups. ZDM is one of the latest WG that has been proposed to the IOF Technical Oversight Board.

2.4. IOF methodology

In IOF, a combination of bottom-up and top-down approaches are used for ontology development. A top-down method is enforced through using a TLO and a suite of mid-level ontologies that provide the necessary high-level and generic classes. A bottom-up approach is also implemented in a sense that several use cases, related to the domain of discourse, guide the development and analysis process. The key terms as well as their related competency questions (CQ), are derived from the selected use cases. Some use cases might be too specific and narrow, and their relevant notions might be more suitable for an application ontology rather than a reference ontology. However, their analysis is necessary in identifying the high-level ontological constructs that are needed to formalize low-level terms that often belong to application ontologies. In a sense, use cases provide the means for bottom-up reference ontology development.

IOF uses a formal set of rules for annotating the ontology. According to IOF's annotation rules, each term should have three types of definitions including natural language definition, semi-formal definition, and first-order logic definition. Natural language definition is primarily prepared for human users and its goal is to provide a clear and human-intelligible definition of the term. The First Order Logic (FOL) definition is the logic-based definition that can be understood and interpreted by software agents.

The semi-formal definition provides a bridge between the FOL definition and the natural language definition. For primitive terms, an *elucidation* is used instead of formal definitions. Primitive terms and relational expressions are often so basic in their meaning that there will be not logically simpler, and thus more easily intelligible, expressions on the basis of which they can be defined in a non-circular way.

Whenever a set of restrictions can be identified to collectively define the *necessary and sufficient* conditions for a term, then both semi-formal and FOL definition need to be provided. Fig. 1 shows the procedure used for linguistic and ontological analysis of terms. More specifically, Fig. 1 presents the workflow steps in order that are required for the linguistic and ontological analysis of terms. The linguistic analysis should result in creation of a consensual natural language (NL) definition. This definition is used as the input for the ontological analysis process.

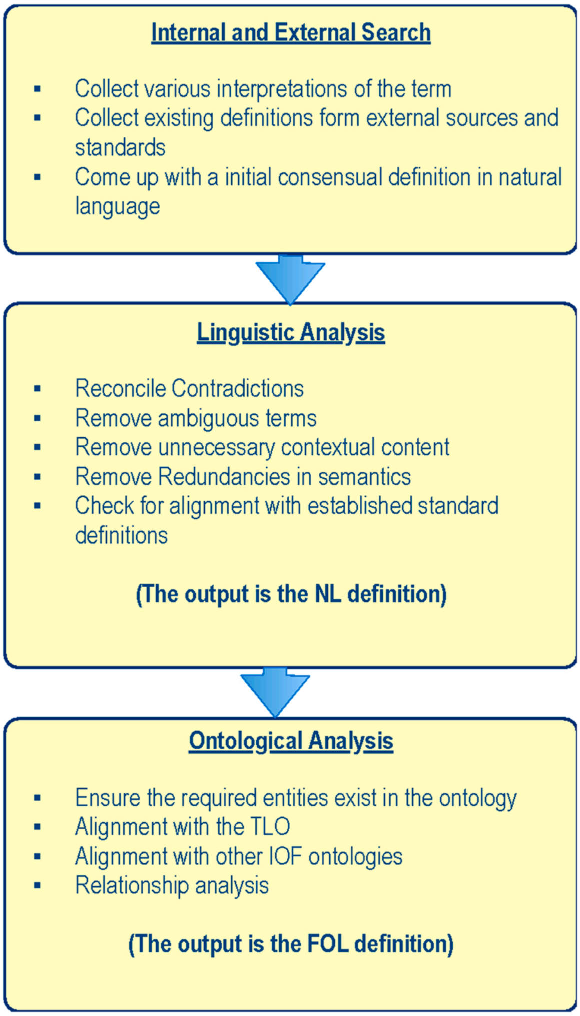


Fig. 1. The procedure for linguistic and ontological analysis of terms.

The term analysis process begins by collecting definitions from the domain experts that participate in working group (WG) activities and several external sources including ISO online browsing platform, relevant domain standards and glossaries such as APICS and other ontology portals such as Ontobee and Bioportal repositories. In some cases, one of the definitions that sufficiently conveys the intended meaning of the term is directly adopted as the natural language definition. In other cases, the candidate definitions will go through some linguistic and semantic pre-processing steps such as disambiguation, reconciling contradictions, removing unnecessary contextual contents, and removing redundancies to arrive at a more refined definition that is more amenable to formalization.

Ontological analysis is a more complex process, and it depends on the type of entity that is under analysis. For example, if the term is a type of a Planned Process (i.e., BFO: process that is prescribed by a plan that the process achieves), then the ontological analysis would include identifying the agents that play a causal role in the process, the plan specification that prescribes the process, the intended objectives, the roles and functions that are realized in the process, pre-conditions and post-conditions (or states), and the temporal instants that identify the boundaries of the process.

The linguistic and ontological analysis procedure is facilitated using Jira issue tracking tool. Using Jira issue tracker, working group members can raise issues against working definitions and formalizations and participate in collaborative development of the ontology. If generic terms that are applicable to multiple domains are identified during the linguistic or ontological analysis process, they are transferred over to the development workflow of the IOF Core Ontology where more generic and abstract terms are formalized and curated. Examples of those common terms include Agent, Resource, Capability, Product, Event, and State.

Fig. 2 shows the overall development life cycle of ontologies in IOF. The output of Term Analysis step is the input to the Final Review Procedure and includes stable natural language definition for each term, and a stable semi-formal definition (for terms with both necessary and sufficient conditions) or stable elucidations for terms that are deemed to be primitive. A key objective of the final review cycle is to drive the definitional content of terms to the *fully-formalized* state, per the IOF technical principles and ontology annotation rules. Some of the criteria used for releasing IOF ontologies include machine readability, conformance to IRI structure and format, and logical consistency as listed in Table 1. Some of these criteria are evaluated automatically through hygiene tests and SPARQL queries.

2.5. Existing ontologies and studies related to ZDM

There are no ontologies currently available with exclusive and explicit focus on ZDM. However, in closely related areas such as quality assurance and maintenance, there exist several ontologies with varying levels of formality that can be reused in development of a ZDM ontology.

One of the most relevant ontologies to ZDM domain is ROMAIN which is a BFO-conformant ontology (Karray et al., 2019). ROMAIN is particularly focused on maintenance management for industrial assets and provides formal patterns for representing notions such as maintenance strategy, degradation, and work order management. ROMAIN also provides reusable constructs for representing defect, nonconformity, and various maintenance states that are within the scope of ZDM. Z-BRE4K is an ontology that is designed to serve as a common reference model for annotation of data related to manufacturing system performance (Cho et al., 2019). The ontology describes the basic entities for modelling shop floor procedures, machinery and their critical components, their failure modes and their criticality, and their signatures of healthy and deteriorated conditions. Some notions with ZDM significance, such as current quality, predicted quality, and failure cause, are represented in this ontology. Another relevant ontology is CDM-Core that is developed according to condition monitoring data model from ISO13372 to semantically annotate sensor data (Mazzola et al., 2022). The CDM-Core work focuses on an asset's performance and has useful descriptions of quality measures and a detailed verification process.

Table 1
Some of the criteria used for releasing IOF ontologies.

Criterion	Requirement	Method of Evaluation
Machine readable form	An OWL file is provided that is conformant with the W3C rdf/xml syntax and the W3C OWL standard.	The OWL rdf/xml file must be processed by a tool among those considered acceptable IOF to verify syntax conformance, or successfully pass IOF tests of same.
IRI structure and format	web ontology forms conform to IOF rules for IRI Structure and Format.	Tested with hygiene tests or SPARQL queries
Logical consistency	The logical content of the OWL file must be logically consistent (i.e. contain no unsatisfiable elements).	The OWL rdf/xml file must be processed by a reasoning tool among those specified by IOF, loaded along with BFO and any other ontology modules on which it depends into the tool, and its consistency/satisfiability tested.
Quality	OWL file conforms with label, definition, and other annotations as specified in the IOF Annotation Vocabulary.	Tested with hygiene rules.

Although the existing ontologies partially cover the ZDM vocabulary, there are still some core ZDM notions that are not properly modeled in any single ontology. It is also important to note that most of these ontologies do not use any axioms which prevents them from being used effectively for reasoning and consistency checking services. The objective of the ZDM ontology is to serve as a single point of reference for the ZDM domain through providing axiomatic definitions and constraints for ZDM terms.

In literature there are some studies that they are utilizing the power of ontologies and semantics for improving the product and process quality. For example, in the domain of additive manufacturing (AM) ontologies have been used for serving as a backbone of the AM data and automatic reasoning is used for facilitating the creation of decision-making apps and algorithms (Sanfilippo et al., 2019). To facilitate the integration of data across the product life cycle, numerous software solutions are being developed. Unfortunately, these systems exhibit a

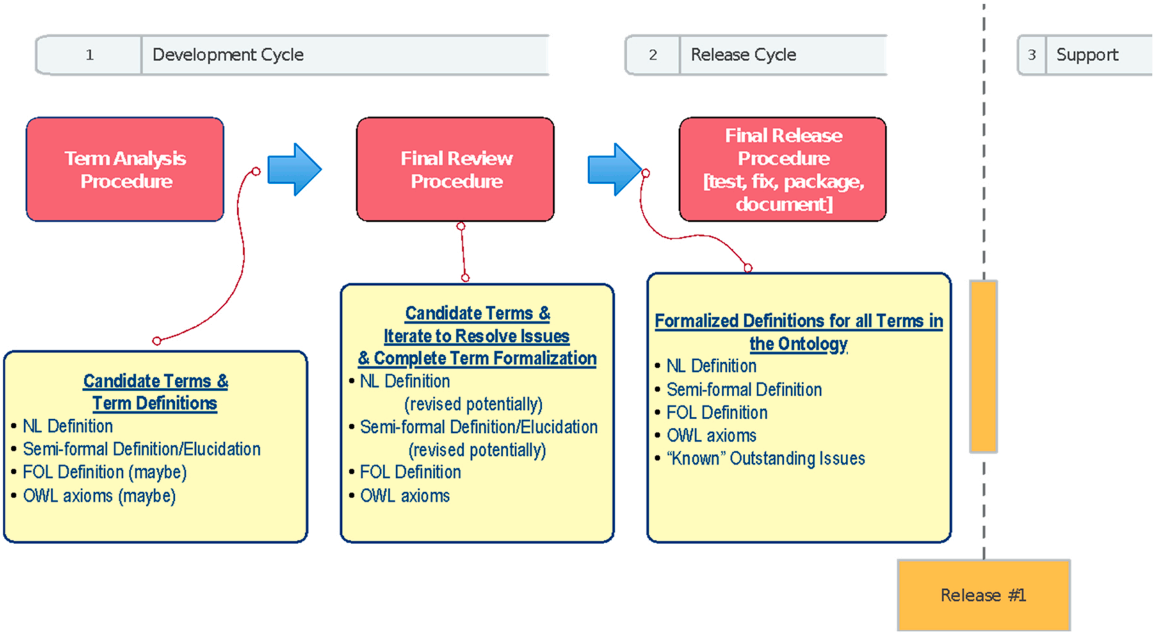


Fig. 2. Analysis, review, and release process for IOF ontologies, OWL: Web Ontology Language.

limited level of interoperability, which causes issues, for example, when various businesses or parts of a business connect. Common ontologies (consensus-based controlled vocabularies) have established themselves as an effective approach for resolving such issues in a variety of disciplines (Mohd Ali et al., 2019). A review study examined how current trends in Industry 4.0 (I4.0) solutions are impacting the growth of manufacturing execution systems (MESs) and looks at the patterns that will shape the advancement of these technologies' next iteration. The observed patterns demonstrate that, as interoperability becomes more of a priority, formal models and ontologies will play an even more crucial role in I4.0 systems and that the next generation of linkable data sources should be built on semantically enriched data (Jaskó et al., 2020).

3. ZDM terminology & ontology

The current section will present the terms that will be used for the construction of the ZDM ontology. Also, in Section 3.2 the ZDM ontology will be presented, and some key features will be analyzed. For the development of the ZDM ontology, the IOF methodology was followed for the proper and sustainable way of development of the ZDM ontology.

3.1. ZDM terminology

Modern ZDM domain is fairly new and in 2020, the foundations of ZDM were defined by Psarommatis et al (Psarommatis et al., 2020b, 2021a). and therefore, there is almost no ontologies focusing on ZDM except two papers by the same author which are not focusing on developing the ZDM ontology but rather setting some preliminary terminology (Ameri et al., 2021; Psarommatis and Kiritsis, 2021). In the current, research work a set of 98 ZDM related terms will be used for the development of the ZDM ontology. This terminology is an outcome of a standardization process by CEN/CENELC and DIN where authors are part of this process. To have a complete vocabulary for constructing the ZDM ontology, the ZDM-specific terms together with generic manufacturing terms such as "factory" or "product" need to be collected and formalized. Those generic manufacturing terms were not defined from scratch but reused from other domain ontologies provided by IOF. Further to that, the ZDM ontology should be BFO, therefore, a set of mid-level terms was used for linking the abstract concepts of BOF to the domain specific concepts of ZDM. Examples of mid-level terms that connect BFO entities to ZDM terms can be found in Table 1. Additionally, the Information Artifact Ontology (IAO) is used to represent information entities. The IAO is a domain-neutral mid-level ontology for representing information entities that stand in a relation of aboutness to continuants and occurrents.

3.2. ZDM ontology

The ZDM ontology was developed using the IOF methodology for developing ontologies and reusing as many as possible terms from already defined IOF ontologies or others and using the BFO as an upper-level ontology. The ZDM ontology currently contains 147 classes, Fig. 3 illustrates the Basic taxonomy of BFO with some additional classes such as Non-conformity, Product and Resource which they belong to the Continuant class of BFO. BFO has to main categories of classes, namely, the "continuant" and the "occurrent".

A Continuant is an entity that persists, endures, or continues to exist through time while maintaining its identity. An Object, such as a machine, a factory, or a person, is the most common type of continuant that can be found in BFO-conformant ontologies. An occurrent is an entity that unfolds itself in time or it is the start or end of such an entity or it is a temporal or spatiotemporal region. Processes are the most widely used sub-types of occurrents.

Most of the ZDM oriented classes are categorized under the "continuant" branch as shown Fig. 4, Fig. 5, and Fig. 6. Fig. 8 demonstrates all the processual classes such as inspection and monitoring that are under the "occurrent" class.

3.2.1. Descriptive information content entity

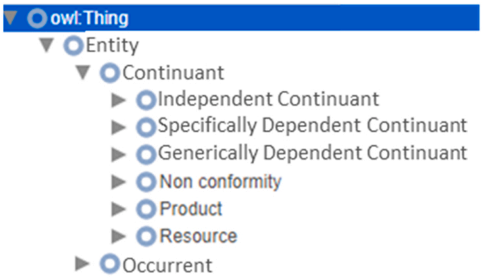
Descriptive Information Content Entity (ICE) is a class that is imported form CCO. It is an Information Content Entity (an IAO class) that consists of a set of propositions that describe some Entity. All measured values that describe the extent, dimensions, quantity, or quality of an Entity relative to some standard or measurement system all instances of Descriptive ICE. Under the descriptive information content entity class, the measured KPIs of a manufacturing system are listed. Those KPIs are those that are related to the ZDM concept, such as defect rate, which is a percentage of products that are out of the defined specifications related to the specific batch. Or rework ratio, which shows how may defected products can be repaired from the total number of defected products. Reparability denotes for how many of the defects that can occur to a product, repair can be attempted.

3.2.2. Directive information content entity

Directive ICE (also imported from CCO) is an Information Content Entity that consists of a set of propositions or images (as in the case of a blueprint) that prescribe some Entity. Procedures, algorithms, requirement specifications, and plan specifications are examples of Directive Information Content Entities (DICE).

The core of the ZDM ontology is under the directive information content entity. Starting with the ZDM strategies which are the foundation of ZDM approach. Those strategies are the "Detection", "Prediction", "Prevention" and "Repair" as defined by Psarommatis (Psarommatis et al., 2020b, 2021a; Psarommatis and Kiritsis, 2018). Also, DICE class also has the "Zero Defect Manufacturing" class which denotes the ZDM approach. The definition of ZDM is as presented in the introduction (Psarommatis et al., 2021a). Furthermore, the class "design for zero defect manufacturing" requires more explanation since it is not completely self-explanatory. This concept was first introduced and defined by Psarommatis (Psarommatis, 2021). Design for ZDM is any method that help in the design and quantification of specifications of any equipment or software that is related to the quality control and assurance (Psarommatis, 2021). Figs. 7–9.

Zero waste is classified under ZDM class because ZDM is not only for

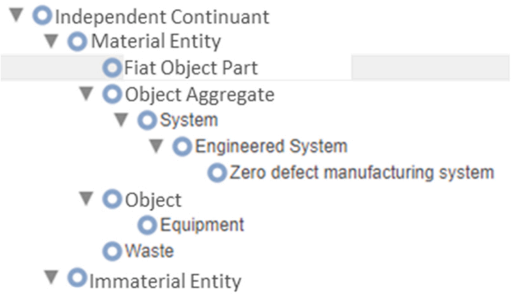


- owl:Thing
  - Entity
    - Continuant
      - Independent Continuant
      - Specifically Dependent Continuant
      - Generically Dependent Continuant
      - Non conformity
      - Product
      - Resource
    - Occurrent

Fig. 3. BOF top levels.

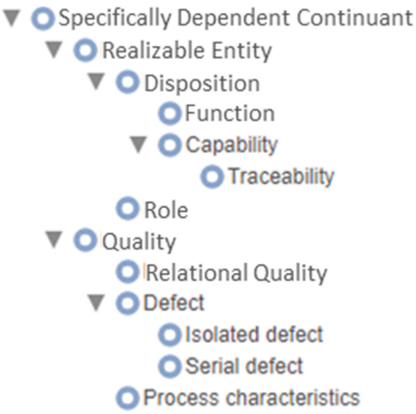
- Continuant
  - Independent Continuant
  - Specifically Dependent Continuant
  - Generically Dependent Continuant
  - Non conformity
    - Process problem
    - Product problem
  - Product
    - Manufactured Product
  - Resource
    - Human Resource
    - Material Resource

Fig. 4. Continuant.



- Independent Continuant
  - Material Entity
    - Fiat Object Part
    - Object Aggregate
      - System
        - Engineered System
          - Zero defect manufacturing system
    - Object
      - Equipment
    - Waste
  - Immaterial Entity

Fig. 5. independent continuant.



- Specifically Dependent Continuant
  - Realizable Entity
    - Disposition
      - Function
      - Capability
        - Traceability
    - Role
  - Quality
    - Relational Quality
    - Defect
      - Isolated defect
      - Serial defect
    - Process characteristics

Fig. 6. specifically dependent continuant.

assuring product quality but also maintaining process quality within the desired levels and therefore eliminate or reduce all types of wastes. Waste is not only material based, but there are also many different types of wastes such as manufacturing time. In the class “Information Entity” two key classes are included with some times confusing definition. Alert is the information that is created when a parameter in the production is out of range, but the products continue to be within specifications therefore some prevention action is required to fix the issue before it creates problem. Alarm is the information that shows that something has happened, and corrective action required.

3.2.3. *Ontology properties*

The goal of the properties (or relationships) is to relate classes to one another to better represent the domain knowledge. Properties are also used in building formal axioms or restrictions when defining classes. Similar to classes, all relational entities need to have natural language definitions to avoid the risk of misinterpretation. Reusing exiting properties provided by other ontologies is a best practice that is often recommended in ontology development efforts. In most BFO-conformant ontologies, the Relations Ontology (RO) is often imported and reused extensively. Some of the RO relations used in the ZDM ontology are listed in Table 2. Table 3.

4. Industrial use case

4.1. *Motivation*

- Generically Dependent Continuant
  - Descriptive Information Content Entity
    - Accuracy
      - Inspection accuracy
      - Prediction Accuracy
    - KPI
      - Defect rate
      - Effectiveness
      - Efficiency
      - First pass yield
      - Repair effectiveness
      - Rework ratio
      - Rolled throughput yield
      - Scrap ratio
      - reparability
  - Directive Information Content Entity
    - 100% inspection
    - Absolute zero defect manufacturing
    - Design
      - Manufacturing System Design
      - Product Design
    - Design for zero defect manufacturing
    - Non destructive inspection
    - Objective specification
    - Plan Specification
      - Manufacturing Operation Specification
      - Manufacturing Process Plann
    - Prevention effectiveness
    - Repair effectiveness
    - Requirement
      - Product Requirement
    - Task Description
    - ZDM strategy
      - Detection ZDM strategy
        - Hybrid detection ZDM strategy
        - Physical detection ZDM strategy
        - Virtual detection ZDM strategy
      - Prediction ZDM strategy
        - Predictive horizon ZDM strategy
        - Predictive maintenance ZDM strategy
        - Predictive time to failure ZDM strategy
      - Prevention ZDM strategy
        - Predictive action ZDM strategy
        - Preventive action ZDM strategy
      - Repair ZDM strategy
        - Correction ZDM strategy
        - Corrective action ZDM strategy
    - Zero defect manufacturing
      - zero waste
  - Information Entity
    - Alarm
    - Alert

Fig. 7. generically dependent continuant.

This section describes an industrial use case to demonstrate how the designed ontology can be used in real life applications. Note that the main focus of this paper is to present the ZDM ontology, and the objective of this section is to showcase how it can be used in an industrial scenario and assess how users perceived it, rather than benchmarking the effectiveness of ontology-based solutions. The use case hereby described illustrates how the zero defects manufacturing ontology can support the development of zero defects manufacturing software solutions in the Zero Defects Manufacturing Platform (ZDMP) (Campbell et al., 2020). ZDMP is a multi-sided, extendable platform integrating a range of components specifically designed to support factories achieving zero defects manufacturing. ZDMP considers two main stakeholders,

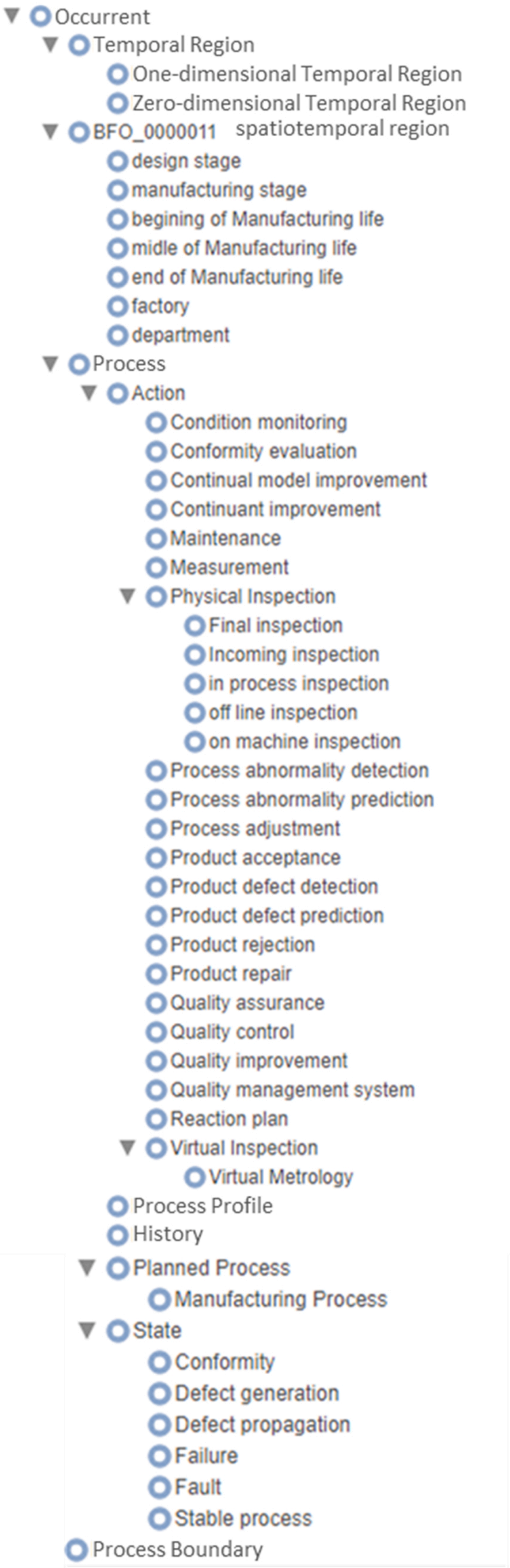


Fig. 8. Occurrent.

namely software developers who develop applications (or zApps) supported on the ZDMP components and aimed at supporting zero defects manufacturing and manufacturing users who use the ZDMP applications and services to ensure process and product quality.

ZDMP envisions a dynamic, collaborative environment where manufacturing users specify their needs for new models and algorithms to solve zero defects manufacturing problems and developers develop new solutions, possibly reusing available open source resources for development. The component that supports collaboration between developers is called “Human Collaboration Hub”: A collaborative environment and software project repository based on Git (Preißel and Stachmann, 2014). Basically, the Human Collaboration Hub enables interactions between manufacturing users and developers as follows. Manufacturing users publish a zApp challenge, a request for the development of a zero manufacturing solution that responds to a specific need. A challenge is basically a Git project that contains a description of the problem and optionally datasets that developers can use to design, develop, train, and validate the solutions. On the other hand, developers create and maintain zApp projects, i.e. Git repositories with the source code of their zero defects manufacturing solutions, solving a problem in the zero defects manufacturing domain, and possibly targeting a challenge published by a manufacturing user. Developers can use different templates, used as skeleton or scaffold to develop their solution. The templates include files to control the Continuous Integration / Continuous Delivery (CI/CD) pipelines used to automate different software development stages (build, test, release).

One of the problems that the PO Designer wants to address is that software developers may have data science skills, but may not be domain experts in every zero defects manufacturing field and every manufacturing sector, and consequently, they might not know which algorithms can be used in a specific zero defects manufacturing use case. Conversely, manufacturing users have in-depth knowledge of the problem domain, but not on the methods and algorithms that are well suited to solve a specific problem. Some examples of competency questions that these stakeholders may have are:

- Is there any model to predict process anomalies in plastic injection machines?
- What algorithms can I use to detect quality errors in food processing?
- What evolutionary algorithms can I use to optimize the set-up of a metal-machining machine?
- Are there datasets to develop and test virtual inspection applications (Dreyfus et al., 2021)?

At this stage, the Zero Defects Manufacturing ontology can be very useful to provide the right orientation to manufacturing users and developers, since it provides common means to represent both zero defects manufacturing problems and solutions as entities, and the relationships between them, and use this knowledge to help stakeholders find problems and solutions in the zero defects manufacturing domain. This is the main motivation behind a second ZDMP component, the Prediction and Optimization Designer (PO Designer). This component implements a search engine supported on a Zero Defects Manufacturing ontology in OWL (McGuinness and van Harmelen, 2004) format. The search engine helps stakeholders identify resources (either datasets useful for development and validation or open source solutions) that can be reused, adapted, and/or composed to address a specific zero defects manufacturing instance. Nowadays there is a huge range of open resources that can be used to develop data-driven analytic solutions for zero defects manufacturing. The main barrier for developers is not the lack of libraries, but knowing the relationship between problems and solutions in the zero defects manufacturing problem domain (when and where to use available solutions), and this is the main problem that the PO Designer tries to alleviate.

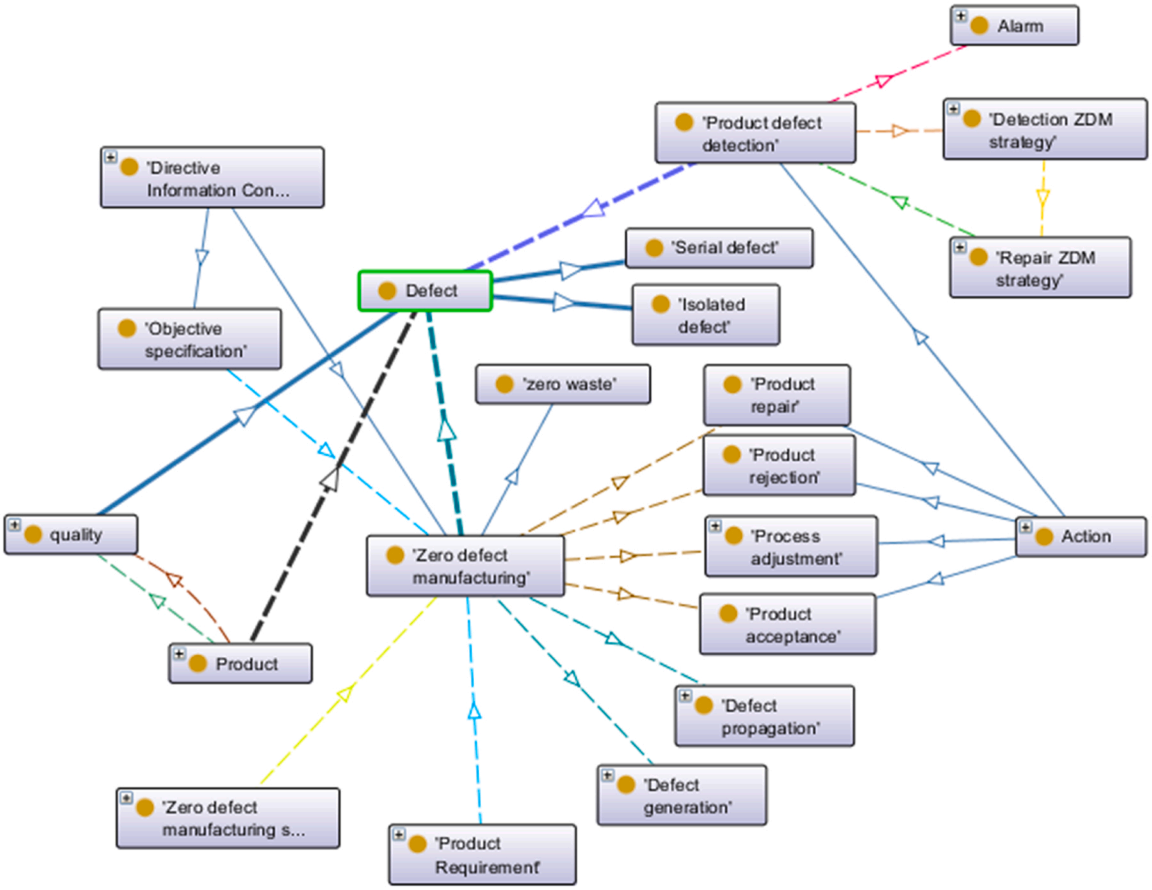


Fig. 9. Defect class with connections.

Table 2
RO relations used in ZDM ontology.

Relationship	Domain	Range	Definition
participates in	Continuant	Process	a relation between a continuant and a process, in which the continuant is somehow involved in the process
has role	independent continuant	Role	a relation between an independent continuant (the bearer) and a role, in which the role specifically depends on the bearer for its existence
Inheres in	specifically dependent continuant	Independent continuant	b inheres in c =Def b is a specifically dependent continuant & c is an independent continuant that is not a spatial region & b s-depends on c

4.2. Functionality

Through the PO Designer, developers can create a project either a completely empty project, a project reusing existing resources, or a project to respond to a specific challenge. At this stage, the PO Designer implements a search user interface component that developers can use to find zero defects manufacturing resources related to a search criteria. The solution will then apply these filters and show a list of the resources that match the search criteria. Users can then view the list of search result and read the description of each item. After reading the descriptions, they can select the resources that they are going to use and create a new project based on this list. At this point, a software generator will use the human collaboration hub backend programming interface to create a new project from a template, import all the selected resources into the new project, and prepare the metadata information and the CI/CD pipeline configurations so that developers can focus on solving the specific problem at hand. This is possible because all the algorithms available in ZDMP are built using a base template that ensures interoperability and composability. In the newly created project, developers can extend, adapt, or just reuse the imported resources, and use the imported datasets to test and validate their solution.

The PO Designer focuses on the labeling of challenges and solutions with children of two classes of the ontology: Sustainability indicators (e.g. downtime costs, carbon emissions, worker training), and the action towards zero defects (e.g. product quality prediction, machine parameter tuning, sequencing optimization). The idea is to use these classes of the ontology to get a semantic description of the use case: With one label of a class under ’Action’ and one label of a class under class ’Indicators’, implicitly, stakeholders get a description of the solution as a tool that implements an action to overcome a defect in the zero defects manufacturing domain. Fig. 10 shows a screenshot of the PO Designer.

In the current version, when a developer adds solutions, a label recommender uses the text description provided by the developer to suggest classes of the ontology (specific children classes as mentioned before). The recommender uses Sentence-BERT (Reimers and Gurevych, 2019) to encode the description of the solution into a sentence embedding vector, which is then compared to the embedding vectors of the terms in the ontology using a cosine distance function. The score measures the semantic similarity between the description of the solution and the terms in the ontology children of the selected classes. The top 3 classes are recommended to the user, who then labels the solution either selecting one of the suggested classes or another class if the

Table 3
Ontology defined properties.

Relationship	Domain	Range	Definition
has defect	Product	Defect	Relation between product and defect to demonstrate that a product can be defected
Detects	Product defect detection	Defect	Relation between product defect detection and defect to demonstrate that the product defect detection can detect defects
Generates Alarm	Condition monitoring	Alarm, Alert	When implementing condition monitoring it generates an alarm when an anomaly is detected
Has accuracy	Equipment	Accuracy	Relation to demonstrate that the ZDM equipment have accuracy, for example a laser scanner has a certain accuracy.
Has Capability	Equipment	Capability	Relation to demonstrate that equipment have different capabilities
Has characteristic	Manufacturing process	Process characteristic	Relation between manufacturing process and process characteristics to demonstrate that each manufacturing process has characteristic which is the quality of the process
Has design	Zero Defect manufacturing system	Design for Zero defect manufacturing	A manufacturing system to achieve ZDM needs to be designed in a certain way, this relation imposes this requirement.
Has effectiveness	Repair ZDM strategy, Prevention ZDM strategy	Repair effectiveness Prevention effectiveness	Repair and prevent ZDM strategies have a certain percentage of effectiveness, which is described by this relation.
Has Equipment	System	Equipment	A system in general is equipped with equipment
Has KPI	System	KPI	Systems have KPI to quantify the performance.
Has quality	Product	Quality	Relation to demonstrate that a product has quality
Has requirement	Detection ZDM strategy	100% inspection	ZDM detection imposes that 100% of the parts being produced need to be inspected
Has state	Equipment	State	An equipment can have different states
Has ZDM action	Detection ZDM strategy, Prediction ZDM strategy	Repair ZDM strategy, Prevention ZDM strategy	When ZDM detection or ZDM prediction is detecting or predicting a defect then ZDM actions are implemented repair and prevent accordingly.
Is updated with	Plan specification	Action	When a ZDM strategy identifies a problem then an action is implemented to the production to compensate the issue, therefore the original plan is updated with the action.
Utilize ZDM Detection	Product defect detection	Detection strategy	To detect a product defect the Detection ZDM strategy should be utilized
Utilize ZDM prediction	Product defect prediction	Prediction ZDM strategy	To predict a product defect the Prediction ZDM strategy should be utilized

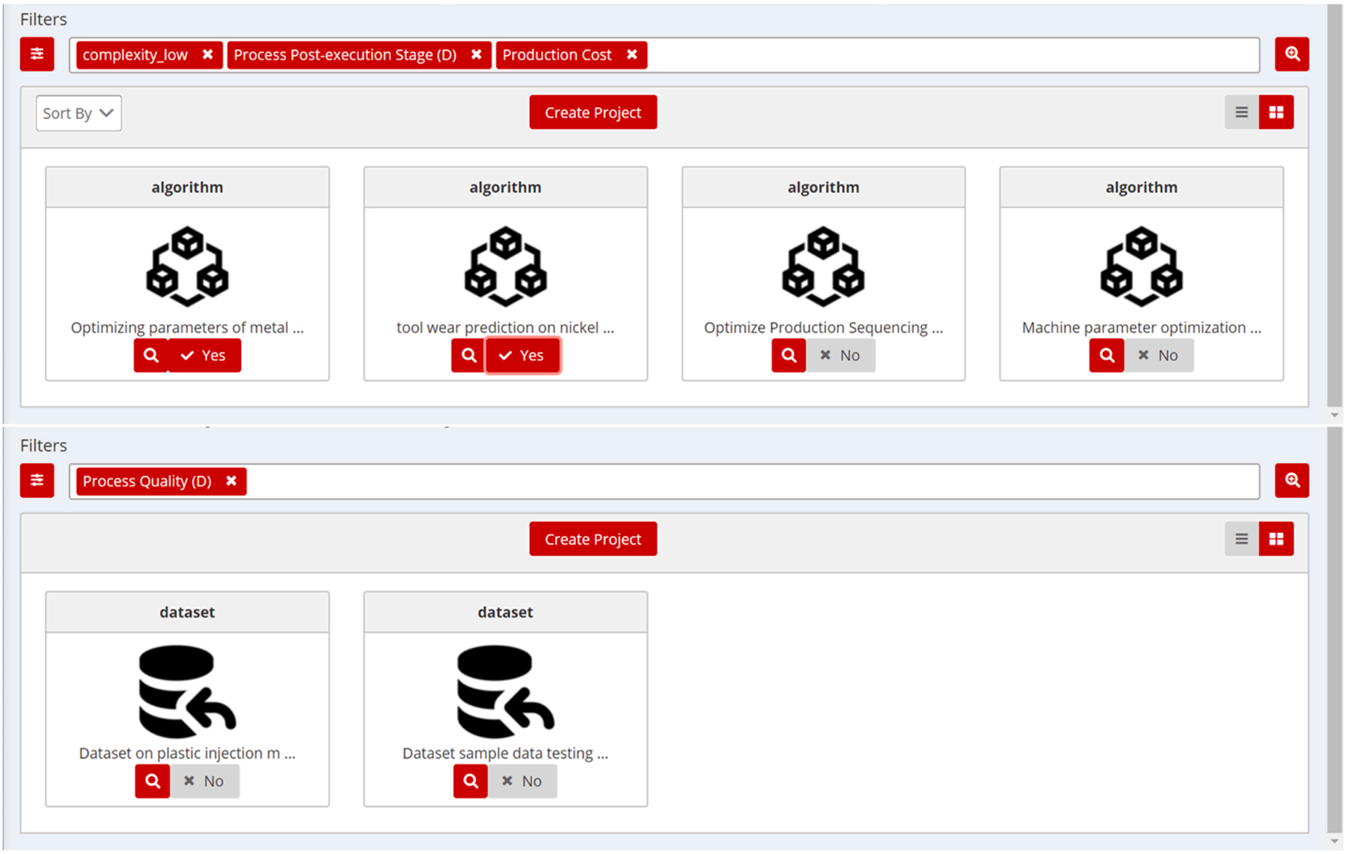


Fig. 10. PO Designer screenshots.

recommendation is not useful.

Later, when other developers or end users want to browse solutions, they can use these labels as filters to filter the available resources, or use a free text search, which is again supported on the recommender described above to sort the results. Fig. 10 shows screenshots of the PO Designer.

4.3. Validation

The validation was supported by the ZDMP Open Call mechanism, which issued two open calls for proposals of innovative zero defects manufacturing solutions based on the platform's components. The aim was to use the ontology-based recommender to label the ZDMP applications submitted to the open call, based on the descriptions included in the project proposals. Specifically, the proposal template included a text field with a maximum length of 500 characters to define an abstract description, and this field was collected and input to the recommender. Thus, the recommender was used to find the children classes of 'Action' that had the best cosine similarity score with the abstract description included in the open call winner proposals. Once that the results were available, the validation focused on assessing how the accuracy of the results and the adequacy of the ontology were perceived by users. To this purpose, the recommender tool was presented to the open call winners, together with the 'Action' labels generated by the recommender for their specific application proposal. The winners then filled in a questionnaire including two questions:

- Would you select any of the proposed labels to tag your solution? (scale from 1 - extremely unlikely to 10 - extremely likely). The aim of this question is to assess to what degree the selected 'Action' is adequate and captures the main objectives of the application.
- Which other tag would you add to your solution (if any)?
- 9 out of 10 open call winners responded to the questionnaire. The average likelihood of selecting the label was 7.56 out of 10. Fig. 11 shows the histogram of the responses. The aim of this question is to collect additional information from zero defect manufacturing use cases as feedback to fine tune the ontology.

Fig. 12 shows the cosine similarity score of the suggested terms against the likelihood of selecting the recommended label. The figure also depicts the linear regression of the best score to better show the relationship between the similarity score and the likelihood of selecting a label.

4.4. Discussion

In general, the results of the questionnaire proved that the defined actions towards zero defects capture most of the use cases proposed by open call winners. Moreover, the results show that there is a high correlation between the similarity score obtained by the recommender and the likelihood of selecting a recommended label. This way, the similarity score provides a quantitative estimation of the quality of the recommendation, which can be used to improve the search experience.

Although in general the results were good, 3 out of 9 recommendations scored 5 or less out of 10. To better improve the ontology, the open call winners that provided low scores were contacted individually to better understand what they missed in the recommendations. These interviews provided actionable feedback to improve the ontology.

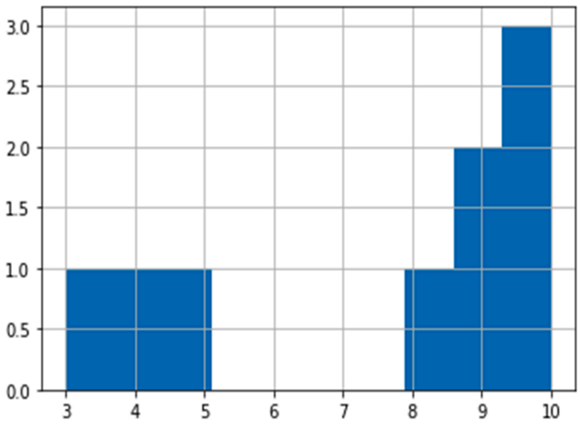


Fig. 11. Histogram of the likelihood of selecting a label.

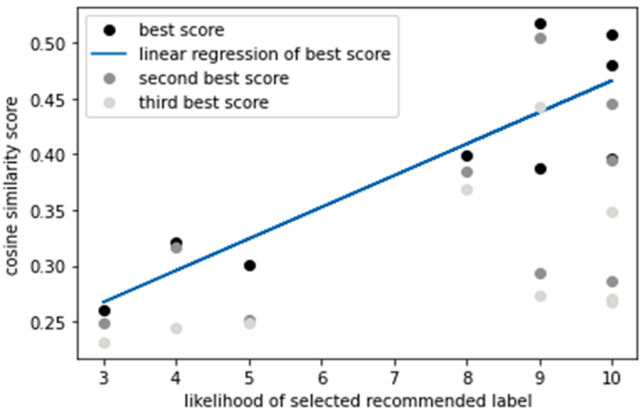


Fig. 12. Similarity score against likelihood of selecting the recommended label.

Additionally, the tags suggested by open call winners that also scored high also triggered discussions to better improve the ontology. More specifically, the main gaps identified during the validation where:

- Data collection: Collecting data to better understand the production process and the quality of products was one recurring topic among the first open call winning projects. One key concept that was missing in the ontology was operator feedback collection, capturing the expert knowledge of operators in the floor plant, either to better understand the process, or to better understand incidents or quality problems. This is actually the scope of one of the open call winning projects.
- Training and upskilling: Operator training and upskilling is clearly one action towards zero defects manufacturing. One of the open call projects applied augmented reality to equipment maintenance training, but there are other actions towards zero defects related to operators training, like equipment operation training to avoid defects, or to reduce process variability.
- Design Update: Finally, there were no actions related to the design phase, so the ontology did not support the description of use cases that act on the design of the product or the process to improve quality.

From these results, these three action categories (data collection, training and upskilling, and design update) and the corresponding children were added to the ontology. Once the new terms were included, the abstract descriptions were repeated to ensure that the recommender selected adequate labels for the use cases with low scores, and that the other recommendations remain unaltered.

5. Conclusions

The current paper was focused on developing an initial version of the ZDM ontology for semantically align multiple software systems that interact in a ZDM ecosystem. The development of the proposed ZDM ontology was performed using the principles introduced by Industrial Ontology Foundry (IOF) and with the use of Basic formal ontology (BFO) as an upper level ontology. The use case validation results show that the combination of Natural Language Processing (NLP) using Sentence-BERT and ontology-based search methods rooted in the zero defect manufacturing ontology is a promising strategy to implement effective search engines for applications in the zero defects manufacturing domain. All the solutions evaluated were effectively mapped to an action towards zero defects defined in the ontology. Furthermore, challenges and solutions can be defined as instances of the identified classes in the ontology to form a knowledge graph that grows in time. This approach to manage the knowledge of challenges and solutions in ZDMP, not only supports the development of new solutions, but also guides strategic decisions for ZDMP (e.g. identify which zero defects problems are not covered by any solution in the platform and establish priorities for the development of new solutions to be published in the marketplace). The current version of the ontology only includes the core classes and relationships between them. In future, OWL axioms will be added to the classes to enable various types of reasoning service including automated classification, consistency checking, and data validation.

Furthermore, the backbone of all reference architectures (RAMI4.0, IMSA) for smart manufacturing and particularly ZDM are data and ontologies constitute the perfect technology for data modeling and knowledge extraction. To create an understanding of industry 4.0 components across industries and nations, new and current reference architectures still need to be harmonized and made compatible. Consistent modeling built on a digital representation of the actual physical components of production systems is a requirement for smart manufacturing, according to all frameworks (Göppert et al., 2021).

Future research will be conducted to validate other important aspects of the ontology. For instance, the labelling of challenge descriptions describing the needs of use cases with children classes of a) product defect or process defect classes, b) zero defects manufacturing KPI classes, c) lifecycle stage classes can provide stakeholders with a description of the challenge as a need to overcome a defect that impacts KPIs in a lifecycle stage. Furthermore, the ontology should be standardized and enriched with not only ZDM information but also be part of a greater quality ontology. This will be achieved by the creation of a dedicated IOF working group. At the same time practical uses of the ontology should be performed to demonstrate the power of ontologies in the quality domain and therefore, convince industries for their performance and capabilities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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