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An ontology to integrate process-based approach in ZDM strategies in a Digital Twin framework

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Abstract: The current context of Industry 4.0 is characterized by challenges that were not present in the past like greater variability, higher customization and greater complexity. To address these challenges and the increasing need from companies to focus on sustainability-related issues is necessary to adopt a quality improvement method. In this paper, the method considered is Zero Defect Manufacturing (ZDM) a "tool" which shows considerable potential, but needs some auxiliary technologies to operate. In this regard, the model proposed is an ontology based on a pre-existent ontology. This new ontology is capable of applying Detect and Repair strategies to go with the creation of a Digital Twin of the product. The realized ontology can be used to support decision-making in an industrial context: in fact, it provides to any operator in the production process, an indication about the quality of the product, also advising some corrective actions if needed, like the repair or the disassembly of the product and the subsequent recycling of the good quality components. To obtain this outcome, an analysis of the literature was performed to determine the gaps present in the literature, then an ontology editor allowed the creation of the ontology and, finally, the ontology was validated in the context of Industry 4.0 Laboratory at the Politecnico di Milano. In this environment, the proposed solution was populated with the data coming from the servers, determining the quality of the product as a function of the state of product components and the condition of one of the assets installed in the production line.

Keywords: Zero Defect Manufacturing, Ontology, Digital Twin, Quality Monitoring, Process-oriented approach, Product-oriented approach

1. INTRODUCTION

Industry 4.0 is a paradigm that developed considerably during the most recent years, subsequently manufacturing industry experienced an important change induced by digitalization. This results from the improvement of advanced technologies that have led to a reshape of the manufacturing systems as highly digitalized and modular ones. Today's manufacturing has also to consider challenges that have further developed with respect to the past, with more management complexity due to the greater product customization and variability in operations. To address these challenges, an advanced Quality Improvement method is claimed. This paper builds upon this claim, considering Zero Defect Manufacturing (ZDM) as an approach acknowledged as promising in this technology-enhanced environment. ZDM is a methodology whose slogan is "doing things right the first time" by leveraging on the technologies of the Industry 4.0 (Caiazzo et al., 2022). This methodology is composed of 4 individual strategies: Detect, Repair, Predict and Prevent, intended both as triggering factors and actions. The triggering factors are represented by Detect and Predict strategies as responsible to identify a quality issue, while Repair and Prevention are the actions activated by the triggering factors (Psarommatis et al., 2022). To be implemented, ZDM follows two parallel approaches: a product-oriented approach and a process-oriented approach (Psarommatis et al., 2022). Even if the two approaches are different, they are both oriented to the same objective, that is the minimization of defects at the end of the production process. In product-oriented approach the starting point of the analysis is the product quality: the quality of the product is measured and it is checked against specifications; if the quality of the product meets the specifications, then the corresponding status of the machines visited for different process steps can be considered healthy; if the product does not meet the specifications, then corresponding machines may be not healthy, thus requiring to be re-calibrated or maintained. Conversely, in the process-oriented approach the health status of the machines visited for the process steps is evaluated and, if it is good, then the produced product will be of good quality. According to Psarommatis and Kiritsis (2021) the selection between product and process-oriented approach is not straightforward since prior investigation is required to select the proper one for each industrial use case.

Considering the process-oriented approach for ZDM as the starting point, this work addresses the implementation of an ontological approach to i) support semantic interoperability and ii) take advantage of the reasoning capability to inform about product defectiveness. The solution is tested and assessed in a Flexible Manufacturing Line (FML).

Therefore, the data collected from the FML are enriched with semantics that enables efficient knowledge extraction and reuse to pursue the integration of product- and process-oriented approaches as well as they are used for inferencing so to properly apply the ZDM strategies of Detect and Repair. Thus, this work is intended as a first investigation to enable the capability to handle both approaches, and finally to fit the production needs in a given production context. The ontology

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is developed to be a core part of a digital twin aimed to mirror and handle the entire product-related information required for the ZDM strategies implementation.

2. SYSTEMATIC LITERATURE REVIEW

A literature review is executed to contextualize this work and identify the gaps to unlock the research opportunities. To reach this objective a systematic literature review methodology has been adopted (Sansone et al. 2017) to collect as much information as possible about the ZDM concept. To this end, the starting point was to define the keywords: Zero_Defect_Manufacturing is selected as keyword to assure a large scope in the literature search in Scopus, IEEE, Web of Science. Hence, 150 articles resulted from the search, further screened according to tile, abstract and content. The overall process is reported in Figure 1.

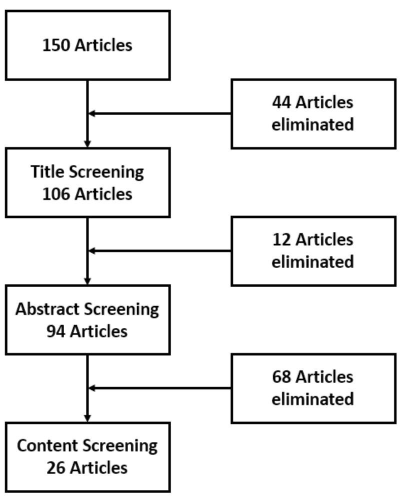


Fig. 1. Screening process

Once these articles have been selected, the analysis phase proceeded with a full-length reading of these papers so as to look for the state-of-the-art in ZDM scientific literature:

- the Repair strategy of the ZDM is not frequently utilized since, to use this strategy, it is necessary to find a tradeoff between the benefit of the strategy and the cost that the introduction of that strategy may determine (Caiazzo et al., 2022);
- In the current state of the art, by looking at the selected articles, the approach usually adopted is the product-oriented approach, it appears easier to implement due to its nature, compared to the process-oriented approach.

This paper specifically addresses those gaps, by integrating a process-oriented approach in the proposed ZDM solution and by considering the repair strategy within it.

On the whole, the overarching objective is the proposal of an ontology, as a decision support system, to enhance detection and repair strategy in ZDM, following a procedure similar to the one expressed in Psarommatis et al. (2023). To realize this ontology some upper-level ontologies, like the top-level ontology BFO (Basic Formal Ontology) (Almeida et al. 2015), the domain-independent ontologies as CCO (Common Core Ontologies) (Jensen 2021) and IAO (Information Artifact Ontology), and, finally, the domain-dependent ontology named ORMA (Ontology for Reliability-centred Maintenance) (Polenghi et al. 2022) have been used. The development of the proposed ontology, called ORMA+, is illustrated in next sections in terms of design and modelling decisions as well as its application for assessment.

3. ONTOLOGY DEVELOPMENT

To build the ontology the METHONTOLOGY (Fernandez et al. 1997) method was utilized since it represents the basic structure for ontology building (Polenghi et al. 2022). In Figure 2 are represented the main phases of the methodology with highlights on the main content of each phase of METHONTOLOGY.

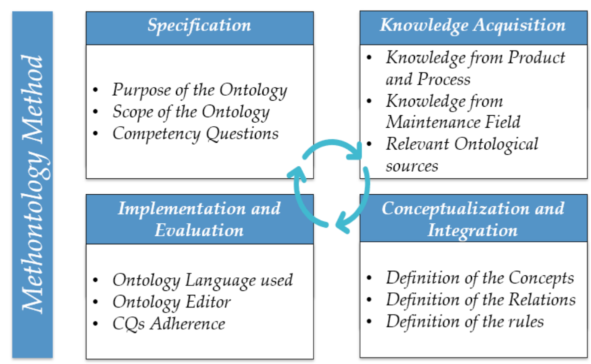


Fig. 2. METHONTOLOGY methodology

3.1 Specification phase

The purpose and the scope of the ontology are defined according to the gaps identified in the literature review.

The domain of the proposed ontology is the industrial or production field, with the purpose of enhancing Detect and Repair strategies in the ZDM context. In this regard, always according to (Fernandez et al. 1997), it is also necessary to define the competency questions (CQ) that the ontology aims to answer. The CQ have been determined in the light of the ZDM features and, in particular, the integration of process-oriented and product-oriented approach:

- **CQ1** What is the quality of a given product that the system realizes?
- **CQ2** Which components of the FML realize a given product?
- **CQ3** Which are the processes required to realize a given product?
- **CQ4** Which product/s is/are not feasible considering both current state of the component/s and the asset/s visited in the processes?

By answering each CQ is possible to verify the ontology as capable to represent the current knowledge of the system.

3.2 Knowledge Acquisition phase

The realized ontology relies on knowledge reuse. In light of ZDM support and integration objectives, knowledge from product and process is an essential element. Considering the definition of process-oriented approach, the knowledge from the maintenance field is also relevant as it enables to integrate, in ZDM, capabilities related to the machines' health assessment and the subsequent maintenance requirements.

Hence, as best practice, upper-level ontologies such as BFO, CCO, IAO are considered, jointly with a maintenance-specific resource that is the ORMA ontology. In particular, ORMA+ ontology considers ZDM while extending the ORMA ontology as the main reference. As reported by Polenghi et al. (2022), the interest of the ORMA ontology is directed mainly toward those companies in which production management is characterized by high flexibility or reconfigurability. In fact, the focus of the ontology is related to those automated production systems having flexible routings, even though it can also be used for configurations having discrete part production with limited flexible routings.
The retrieval of knowledge from aforementioned sources, applied in view of the needs of the functioning of the FML of the Industry 4.0 Lab, permits to balance of the terminology used as well as selecting appropriate terms for the ontology.

3.3 Conceptualization and Integration phase

Once the ontological and non-ontological knowledge has been collected, it is necessary to provide a definition of the terms included in the ontology and the relations that hold among them. For the sake of completeness, the overall ontological model is later described in section 4, as it is the major contribution this research work proposes.

3.4 Implementation and Evaluation phase

The ontological model is implemented in OWL (Web Ontology Language) since this language supports reasoning, and the used ontology editor is Protegé because it is open-source and allows the installation of several plug-ins to better investigate the ontology characteristics. In this phase, to evaluate the ontology, its adherence to the competency questions has been verified using SPARQL queries and Snap SPARQL queries. For the implementation of the ontology, a python code was utilized to collect the data coming from the FML. These data, once converted into a CSV file, have been utilized as input to populate the ontology to check the quality of the realized product in considering the rules and the relations present in the ontology.

4. CONCEPTUALISATION OF THE ORMA+ ONTOLOGY

The ORMA+ ontology has been conceptualised and integrated stemming from the reused sources. Different concepts were then defined, also in light of their adoption in the FML of the Industry 4.0 Lab. The main concepts are hereafter presented.

- The Assembly class, shown in Figure 3: "an Object Aggregate which consists of fitting together of the manufactured parts into a complete machine, structure, or unit of a machine".

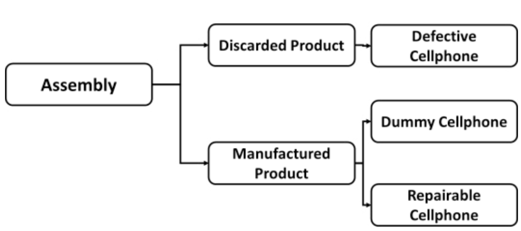


Fig. 3. Assembly class in the ORMA+ ontology

- The Quality class, shown in Figure 4: "a quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized".

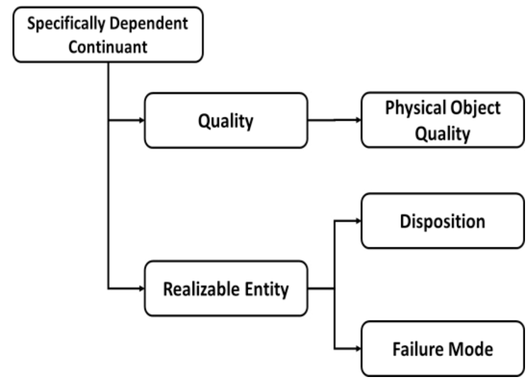


Fig. 4. Quality class in the ORMA+ ontology

- The Asset class, shown in Figure 5: "the artifact performing space and species processes on products, tools and pallets, i.e., their movements as well as the changing of their shape and dimension, respectively".

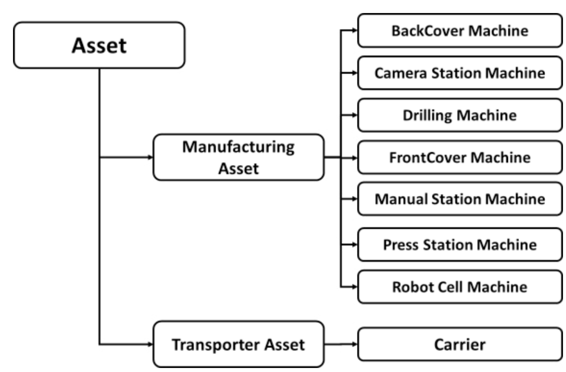


Fig. 5. Asset class in the ORMA+ ontology

- The Process class, shown in Figure 6: "p is a process, p is an occurrent that has some temporal proper part and for some time t, p has some material entity as participant".

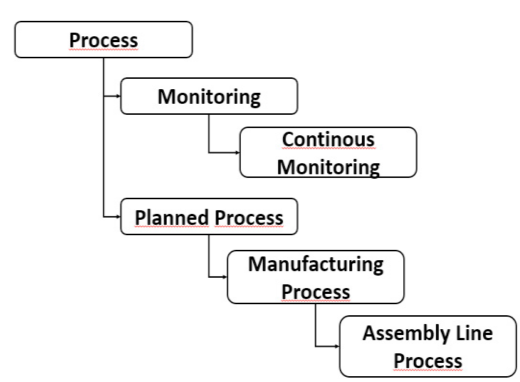


Fig. 6. Process class in the ORMA+ ontology

Where these concepts definitions are taken from already existing ontologies like the BFO, the ORMA and the IOF ontology or were defined by the author of this paper.

5. IMPLEMENTATION AND EVALUATION

In this section, the last phase of the research methodology is faced, which is the implementation and evaluation. This phase includes the implementation of ORMA+ and its evaluation, based on the validation of the logic of the ontology and the adherence to the competency questions. The proposed ontology has been populated using as test bench the FML present in the Industry 4.0 Lab at Politecnico di Milano.

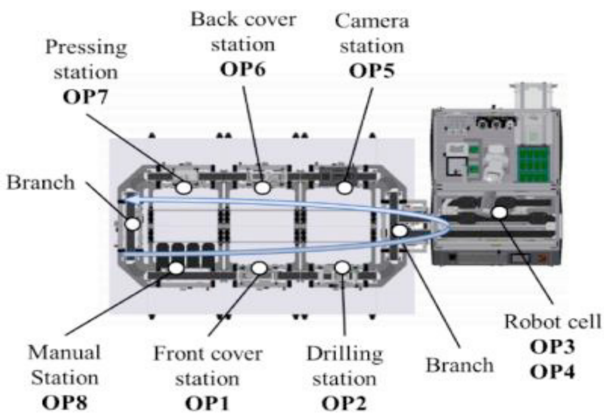


Fig. 7. FML at the Industry 4.0 Lab at Politecnico di Milano

This line has seven workstations, each one performing an activity necessary for the assembly of the final product. The workstations are shown in Figure 7.

For the implementation and evaluation of the ontology, six different scenarios have been considered. These scenarios, selected to demonstrate the potential of the ontology and the way it works, can be divided into three cases according to the quality of the final product in the FML of the Lab, namely the *Dummy Cellphone*, the *Repairable Cellphone* and the *Defective Cellphone,* as listed in Table 1.

Table 1. Design of Experiment

	Good State Component	**Intermediate State Component**	**Bad State Component**
Good Operating Condition	*High quality Cellphone*	*Repairable Cellphone*	*Repairable Cellphone*
Bad Operating Condition	*Repairable Cellphone*	*Repairable Cellphone*	*Defective Cellphone*

The meaning of the different types of cellphone are the following:

- the *Dummy Cellphone* (named *High quality cellphone* in Table 1 to underline that this is the cellphone with highest quality) represents the case of an *Assembly* with *Good Quality* or *Regular_Assembly_Quality*, so an *Assembly* which has *Good_State_Components* and is processed by an *Asset* with *Good_Operating_Condition*;
- the *Repairable Cellphone* represents the case of an *Assembly* with *Intermediate Quality* or *Repairable_Assembly_Quality,* so an *Assembly* which may present one of the following characteristics: 1) an *Assembly* which has *Good_State _Components* and is processed by an *Asset* with *Bad_Operating_Condition;* 2) an *Assembly* which has at least one *Intermediate_State _Component* and is processed by an *Asset* with *Good_Operating_Condition;* 3) an *Assembly* which has at least one *Intermediate_State _Component* and is processed by an *Asset* with *Bad_Operating_Condition;* 4) an *Assembly* which has at least one *Bad_State _Component* and is processed by an *Asset* with *Good_Operating_Condition*;
- the *Defective Cellphone*, instead, represents the case of an *Assembly with Bad Quality* or *Defective_Assembly_Quality*, so an *Assembly* which has at least one *Bad_State _Component* and is processed by an Asset with *Bad_Operating_Condition*.

Therefore, to establish the quality of the products a combination of product and process-based approach has been utilized. As a matter of fact, once the production process is terminated, the data regarding the operating condition of the asset under examination, therefore, the state of the drilling machine of the FML and the state of the components of the product have been retrieved and then evaluated by the ontology. By analysing the data of the overall process, it is possible to determine the state of the product components and the operating condition of the drilling machine and, consequently, it is possible to determine the characteristics of the product like the product quality, the assembly process operated and the product class. Overall, the knowledge obtained from the ontology is used to decide if the product obtained can be sold, if it has to be repaired or if it has to be discarded. This choice was made in order to reconcile the product-oriented approach with the process-oriented one, according to the gaps resulting from the literature findings.

5.1 Implementation of the Ontology

The deployment of the integrated solution is pursued to support the application of ZDM adoption. For this reason, the ontology is made operative by interacting with the assets and sensors installed in the FML to determine the product quality. To this end, during the experiments in the FML, six individuals have been generated into the physical line and have been correspondingly digitally mirrored in the ontology to represent all types of products the FML could realise.

To implement the ontology in the FML is necessary to collect the data coming from the line and, to fulfil this activity, a Golang code has been utilized. As soon as all the data correlated to the process (and the required assets) are collected in a local database, they are converted in a CSV file and a python code is executed in order to retrieve these data and to populate the ontology, consequently determining the quality of the product produced by the line. This quality assessment happens during the runtime of the line. The workflow is depicted in Figure 8.

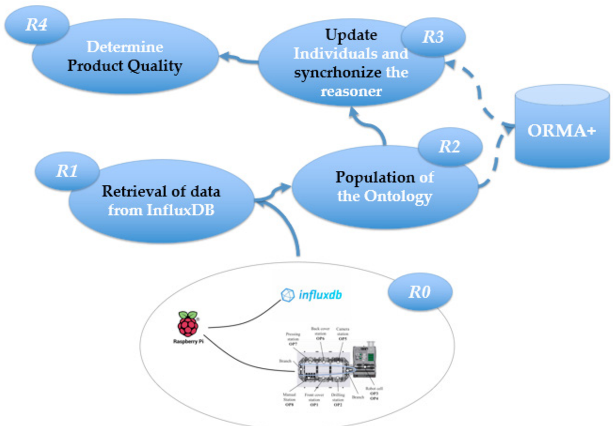
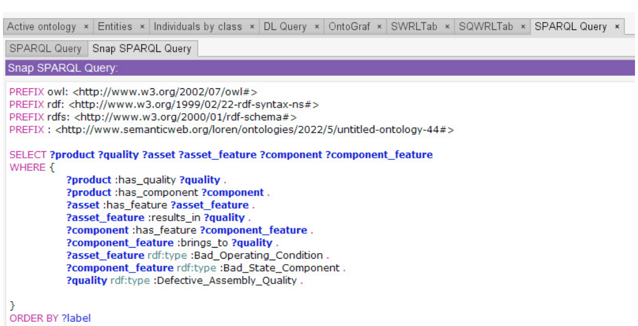


Fig. 8. Ontology Implementation in the FML

5.2 Evaluation of the Ontology

After the implementation of the ontology, it is necessary to evaluate it to see if any discrepancy in the structure of the ontology is detected, by considering the individuals generated in the Implementation phase. These individuals have been used to verify the adherence of the ontology to the competency questions set in the *Specification phase* and, to do so, some Snap SPARQL queries have been used to answer the competency questions.

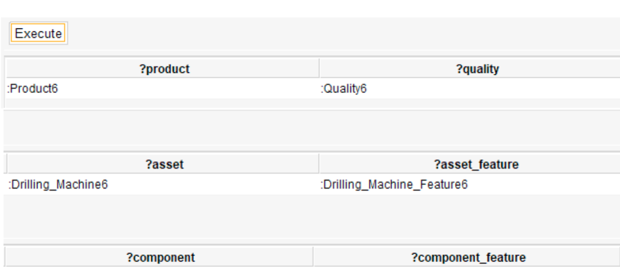



```
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX : <http://www.semanticweb.org/loren/ontologies/2022/5/untitled-ontology-44#>

SELECT ?product ?quality ?asset ?asset_feature ?component ?component_feature
WHERE {
        ?product :has_quality ?quality .
        ?product :has_component ?component .
        ?asset :has_feature ?asset_feature .
        ?asset_feature :results_in ?quality .
        ?component :has_feature ?component_feature .
        ?component_feature :brings_to ?quality .
        ?asset_feature rdf:type :Bad_Operating_Condition .
        ?component_feature rdf:type :Bad_State_Component .
        ?quality rdf:type :Defective_Assembly_Quality .

}
ORDER BY ?label
```

Fig. 9. Snap SPARQL query for the CQ4



?product	?quality
:Product6	:Quality6

?asset	?asset_feature
:Drilling_Machine6	:Drilling_Machine_Feature6

?component	?component_feature
:PCB6	:PCB_Feature6

Fig. 10. Query results

In Figure 9 is shown the query for CQ4. The query permits the identification of which are the elements inside the ontology that belong to the *Defective Cellphone* class. Indeed, this search is executed by looking for the elements that belong to the *Bad_Operating_Condition* class, the *Bad_State_Component* class and the *Defective_Assembly_Quality* class that are connected to the element belonging to the *Defective_Cellphone* class. So, when this query is executed, it is possible to determine the *Defective Cellphone* as well as the *Bad_Operating_Condition asset*, the *Bad_State_Component PCB* and the *Defective_Assembly_Quality* quality, as shown in Figure 10.

After having tested the ontology with the competency questions, it is possible to draw some conclusions:

- First of all, the internal logic of the ontology shows no signs of inconsistency, since it is possible to launch the internal reasoner of the ontology without reporting any error at the logical level.
- The created ontology demonstrates to be able to represent the knowledge inside the system, such as, what products are made and what characteristics these products have. In fact, it is possible to determine the quality of a given product, and the manufacturing process/es used or the component/s that make/s up this product, as well as their status (being either good, intermediate or bad as in the planned scenarios).

After being tested through competency questions, it is then possible to conclude that the full solution deployed in the FML of the laboratory, intended as a preparatory step, can be ready for industrial deployment to support companies in ZDM implementation in their shop floors.

6. RESULTS AND DISCUSSION

Stemming from the results of the laboratory application, it is possible to elaborate over a couple of shreds of evidence.

First of all, this laboratory demonstration shows the capability to interpret and analyze the data coming from the servers of the FML to obtain the results seen during the ontology evaluation phase, like the quality of the product or the components that constitute the product and so on.

Secondly, worth citing, is that the proposed solution has shown that the ontology is able to execute some real-time complex reasonings to discover if the quality of the product is good or if it is necessary to repair or disassemble it. Therefore, thanks to this tool it is possible to help/improve decision-making by aiding companies to make the correct decisions avoiding the delivery of defective products to an eventual customer.

Finally, it is possible to sum up the potentialities of the ontology, as observed in the demonstration, in the following way:

- The aim of the ORMA+ ontology is to provide an instrument which can help companies to improve decision-making in quality management at the shop floor level.
- In the ontology, the ZDM strategies of Detection and Repair have been integrated to make it more extended and complete, introducing a triggering factor and triggering action jointly dealing with specific situations like the repair of one or more components.
- A recycling activity is also integrated and supported by the ontology through the disassembly process; this is meant for increasing the potentiality in the innovative aspect of the ontology, suggesting a step

beyond the ZDM strategy in its pure definition toward a "sustainable" ZDM strategy.

As a final reflection, it is worth remarking that ontologies are expected to play a significant role in the future for several manufacturing industries, given that data are expected to continuously rise up; hence, their semantically coherent integration is fundamental as well as the capability to extract more and more information to generate knowledge for decision-makers. Indeed, the role of an ontology like the one developed in this work is to increase cognitive ability, and this will be an essential feature in the future of manufacturing systems, considering the challenges due to the product variations and flexibility, and hidden complexity therein.

This research aims at pursuing, in the long run, the development of Cognitive Digital Twins, an extension of the concept of Digital Twins well adopted in the current industrial and scientific practice. Specifically, ontologies do represent one of the core part of cognitive digital twins, as they enable cognitive ability thanks to the reasoning capabilities. Hence, this research work may be seen as a first attempt to use ontology in real-time in an industrial environment to make the concept of Cognitive Digital Twin a reality.

7. CONCLUSIONS

This work aimed at creating a tool that could be used within an industrial context to help an operator make the right choices in quality management at the shop floor level, based on the real-time reasonings produced by the ontology. The major research contribution can be summarized as the development of an ontology to adopt both a process- and a product-oriented approach, in order to finally apply the ZDM strategies of Detect and Repair. As a matter of fact, the Detection strategy is applied to determine the state of the product's components or the state of an Asset visited along the process due to the predefined production cycle. In this way, it is possible to verify if it is necessary to adopt a Repair strategy or, if the product is defective, if it is possible to disassemble the product to retrieve the recyclable components. Thanks to the use of these two ZDM strategies, it is then possible to augment the decision-making capability of the operators and finally avoid the delivery of defective products to an eventual customer.
Even though the results are promising, limitations exist in the ontological modelling and the technological deployment. As a matter of fact, the ontology could not manage multiple (alternative) process cycles a product may have. Therefore, ORMA+ is limited in managing the knowledge in situations where a product may be realized by different machines of the same type in the same process step. From the technological deployment side, the Digital Twin obtained is a digital copy of the product which requires the presence of an operator to actuate the decisions based on the results of the ontology; this is due to the lack of the necessary instruments built-in the line to perform such operations in an automated control loop. Henceforth, the Repair and Disassembly actions theorized in the validation of the ontology have been just introduced as proof of concept.

Overall, future work will enable the realization of a more complete ontology, embedded as core part of a Digital Twin. This should be achieved by also extending the scope of monitored data both for the products and processes in the manufacturing system where the Digital Twin is used.

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