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EXECUTIVE SUMMARY OF THE THESIS

Development of ORMA+ Ontology toward Zero Defect Manufacturing in the Digital Twin Framework

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

AUTHOR: LORENZO GHEDINI

ADVISOR: MARCO MACCHI

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Introduction

Industry 4.0 is an industrial paradigm that developed considerably during the recent years and, as a matter of fact, in the most recent period, the manufacturing industry has seen an important growth and change. This change is the result of the improvement of certain advanced technologies, that have led to a reshape of the manufacturing system which, at the moment, presents itself in the current and expected perspectives in the future as highly digitalized and modular.

Today's manufacturing has to consider challenges that weren't there in the past such as: greater product customization and greater complexity. In this environment, therefore, in order to maintain a competitive advantage, it is important to improve the quality of the products and to limit the number of defective items as much as possible, even in a context of high production customization. For this purpose, it has generally assumed vital importance to enhance the quality improvement (QI) methods.

There are several Quality Improvement methods that can be "traditionally" adopted in an industrial plant and that can provide an excellent result such as: six sigma (SS), lean manufacturing (LM), theory of constraints (TOC), and total quality management (TQM). These have been widely used by manufacturers for more than three decades. However, these "traditional" approaches present a criticality, they do not leverage those technologies that make possible to realize things that in the past would have been impossible to realize. For this reason, an approach more recently acknowledged and considered particularly promising in this technology-enhanced environment is Zero Defect Manufacturing (ZDM), a methodology that has as its objective "doing things right the first time" and could achieved by leveraging on the technologies of the Industry 4.0. Therefore, in this thesis work, the following tools will be used together with this methodology, to investigate a possible path for the enhancement: the Digital Twin and the Ontology. The Digital Twin (DT) concept has gained a lot of attention by the industrial communities and the academia in the recent years. For this concept there is not a clear and consolidate definition, but it is still possible to define the core of this methodology: it is the mirroring of a physical asset, enabling data processing for the optimization of a production system or, more generally, a technical system. In particular for this thesis work the role we are going to consider is a specification of the Digital Twin concept, which is the Cognitive Digital Twin. This is a Digital Twin characterized by the augmented semantic capabilities. The semantic capabilities we are going to consider for the Digital Twin will be provided by an Ontology, an element of the "symbolic" artificial intelligence which can be defined as "a formal description of all the entities in a domain and the relations existing between these entities". In particular the Ontology is used to describe an area of interest by listing the related concepts and relating them in the appropriate way.

Literature review and research design

A Literature review is executed to contextualize this thesis work, hereafter it is checked if there are some gaps that emerge from the literature in order to unlock research opportunities and motivate this research. To reach this objective a *systematic literature review* methodology has been adopted [1] in order to collect as much information as possible about the Zero Defect Manufacturing concept. To this end, the starting point of this work of literature was to define the key-words to find specific articles among several fields of science and technology. The *key-word* selected for this purpose was: **Zero_Defect_Manufacturing,** which once inserted in the database of Scopus, IEEE and Web of Science gave 150 articles as result. Then to select the pertinent articles the following methodology was adopted:

1. Title screening
2. Abstract screening
3. Content screening

After this screening process the number of articles retrieved were 26. Once these articles have been selected, the analysis phase proceeded with a full-length reading of these papers. The objective was to look for useful information to be used in order to build an adequate knowledge background to finally motivate the objective of the thesis work by finding the gaps present in the literature. This thesis proposes to fill those gaps by introducing an ontology model, the ORMA+ ontology. Accordingly the following objectives, based on the gaps found in the literature, have been identified:

- *Main Objective*: Creation of a Digital Twin using an Ontology in order to enable a cognitive capability to apply a Detection and Repair strategy to finally pursue the objective of a ZDM.
- *Secondary objective 1*: In the Literature it is shown how the Repair strategy of the ZDM is not frequently utilized because in order to use that strategy is necessary to find a tradeoff between the utility of the strategy and the cost that the introduction of that strategy may comport. The proposed solution therefore may think of a way to utilize a Repair strategy.
- *Secondary objective 2*: It has been observed that in the literature there are several papers in which an application of a ZDM strategy was presented in different sectors. This may make it difficult to understand which tools/techniques can be used and the requirements necessary to obtain a ZDM in a more general sense. The proposed solution may then include a standardization of the ZDM terms and definitions, helpful in a sectoral independent definition of ZDM-related concepts.
- *Secondary objective 3*: In the eligible articles, no unified procedure for data collection, management and elaboration is provided in a unified framework. So it can be interesting to provide a solution able to provide such structure.
- *Secondary objective 4*: In the eligible articles the approach usually utilized is a product based approach since it appears easier to implement due to its nature. This thesis wants to complement this approach with a process oriented one: this further objective advances the possibility to utilize a process

oriented methodology in the overall solution proposed by the work.

Based on these research objectives and considering the expected support for the operator/decision maker, a set of competency questions, that the ontology needs to answer, can be formalized. This are used to qualify that the ontology is able to represent the current knowledge about the system. The competency questions are hereafter reported:

- **CQ1** What is the quality of the pieces that the system realize?
- **CQ2** Which components realize the product?
- **CQ3** Which are the processes required to realize product x?
- **CQ4** Which product/s is/are not feasible considering the current component/asset state?

Model development

In order to realize an ontology able to fulfill the gaps found in the Literature and able to answer the competency questions defined above, the Methontology [2] method was utilized. Following this methodology, the ORMA+ ontology was created, using, as the backbone of the ontology, the BFO, the IAO, the CCO and the ORMA [3] ontology. This respects the criterion of knowledge reuse recommended in the ontology engineering as good practice.

The following main concepts were defined:

- The Product class: "an *Object Aggregate* which consists of fitting together of the manufactured parts into a complete machine, structure, or unit of a machine".
- The Quality class: "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".
- The Asset class: "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".
- The Process class: "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".

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

The entire ontology is fully described in the thesis work, starting from the above listed main concepts.

Validation of the ORMA+ Ontology

To validate the proposed solution the Industry 4.0 Laboratory at Politecnico di Milano was utilized as test-bench using the FML present in there.

This line has seven workstations and each one of them performs an activity necessary for the assembly of the final product. The workstations are:

- Manual where the pallet is put on the conveyor and the product is removed from the line at the end of the process;
- Frontcover where the front cover of the smartphone is put on the product;
- Drilling where the drilling of the cover is simulated;
- Robot Assembly that assembles PCBs and fuses on the cover;
- Camera Inspection that checks if the components are compliant with respect to the workplan expectations;
- Magazine Back that releases the back cover on the product; Press that presses the back and front cover together in order to obtain the final product.

This line is used as test-bench to validate the Ontology. To validate the ontology it is necessary to identify all the possible scenarios that the ORMA+ considers: *Dummy Cellphone*, *Repairable Cellphone* and *Defective Cellphone*. These three categories correspond to the cases of *Good Quality*, *Intermediate Quality* and *Bad Quality*. In these scenarios a combination of Detection and Repair strategy are used.

- In the *Dummy Cellphone* case, for example, the strategy adopted is Detection since there is no need to Repair the Product.
- In the *Repairable Cellphone* case, as the name suggests, one or more components are not conform but can be repaired in order to make them conform and so a combination of Detection and Repair strategy are used.

- In the *Defective Cellphone* case instead the quality of the product is insufficient and the cost to Repair it is considered too big to be convenient and so the Product is discarded. In this last case a disassembly operation is performed in order to retrieve those components whose quality is sufficiently good to be used for other Products.

Population of the ORMA+ ontology

Once the logic of the Ontology is verified, the ontology has been populated with the data coming from the Flexible Manufacturing Line in order to verify if the ontology can be utilized in a real industrial context. Two populations are executed:

- in the first case, the data coming from the FML were converted in a CSV file and they were utilized in order to populate the ontology;
- in the second case, the population of the ontology has been executed with a CSV file realized by the author of this thesis work in order to show all the potentialities of the ontology, overcoming the limits from the current physical installation of the Lab.

In the first case, the population was performed leaving the line free to act, thus allowing to obtain all the data relating to the complete process. These data are analyzed by the ontology, which carries out the necessary reasoning when the production process is concluded. Once the data are elaborated, the results provided by the ontology are the quality of the product obtained and the state of the product components. However, the line at the Laboratory is not equipped with the necessary instruments to make and act upon real-time decisions based on the results shown by the ontology, as the repair and the disassembly process cannot be actuated in the physical workplace. For this reason, even if the ontology recognizes that a product have one or more components that need to be repaired or to be disassembled, these operations cannot be actually performed.

In the second case a new python code for the population of the ontology is developed considering an enhanced FML. For enhanced FML is intended a line characterized by the necessary instruments to operate in real time on a product, which is being processed by the line. Infact, the ontology developed in this thesis work is already able to operate in real time to manage the repair and disassembly process of an eventual product that requires it. Instead the FML in the Laboratory of Industry 4.0 at Politecnico di Milano has not the instruments to cover the entire process steps of the ontology, including the repair and disassembly process. For this reason a new python code and CSV file have been developed in order to simulate the behavior of an hypothetical Repair and Disassembly station present in the FML.

Results and Discussion

In this chapter the results obtained from the population of the ontology and the validation of the ontology will be discussed.

For what concern the validation of the ontology, in the light of the results obtained from the scenarios considered, the following consideration is worth doing:

- The goal of the ORMA + ontology is to help any operator to act accordingly to the results obtained from the ontology. As a matter of fact by running the reasoner when the product arrives at the Manual Station, it is possible to determine the condition of the drilling machine and the state of the components that make up the product, determining, in this way, the quality of the produced product. Thanks to this tool it is then possible to help/improve decision making by aiding an eventual operator to make the correct decisions, finally avoiding the delivery of defective products to an eventual costumer.

For what concern the population of the ontology, two populations were executed. For the first case the following consideration can be made:

- The main outcome it is possible to derive from the first population is that the proposed solution can be implemented in a real industrial context. As a matter of fact the ontology is able to interpret and analyze the data coming from the servers of the FML in order to obtain the results seen during the ontology validation phase, like the quality of the product or the components that constitutes the product and so on.

For what concern the second case instead this was executed with the aim to show all the potentialities of the ontology in the case the line was entirely characterized by the needed instruments in order to perform a real time operation on the product. So the following consideration can be made:

- In this case the proposed solution has shown that the ontology is able to execute some real time complex reasonings like the repair or the disassembly of a product. In fact, the ontology is able to determine if a product needs to be sent to a repair station, therefore, stopping the production process and waiting for the part to be repaired and reinserted into the line before continuing the production process. At the same time, the ontology is also able to determine if the product obtained is defective and so if it is necessary to execute the disassembly of the product, keeping only those components whose quality is sufficiently good to be re-used for another production process.

Conclusions

Based on the performed activities an overview of the research contribution achieved is reported:

- Fulfillment of the Main Objective: The ontology realized permits to develop a Digital Twin of the product obtained by the FML and, when certain conditions are met, to 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 component or the state of the Asset. 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 strategies, it is then possible to validate the proposed solution and to avoid the delivery of defective products to an eventual costumer, since it is possible to determine the quality of the product and help the operator to make the correct decisions.

- *Fulfillment of the Secondary Objective 1:* In this thesis work the Detect strategy was used since this strategy is the most documented and used in the literature, therefore the use of this strategy makes the ontology conform to what was found in the literature. At the same time, however, given the versatile nature of the ontology, the Repair strategy was also introduced in the proposed solution in order to make the ontology more extended, innovative and complete, exploiting a combination of triggering factor, the detection strategy and triggering action, the Repair strategy. After the validation of the ontology there is no way to tell if this combination helped solving this trade-off analysis, but it has been demonstrated the possibility to integrate the Repair strategy in the entire approach to try to solve this issue.
- *Fulfillment of Secondary Objective 2*: The use of an ontology has proven to be fundamental since the ontology in itself involves the introduction of a standardization of the terms and the introduction of a series of definitions, which can make this proposed solution also applicable to other contexts. In fact, one of the key points of the ontology is the Knowledge Reuse; for this reason it is possible to use the knowledge present in the ontology, about ZDM, to construct a new specific solution for any new context.
- *Fulfillment of Secondary objective 3*: In order to cope with this aspect the solution proposed has been validated in a simulated environment where the population of the ontology is realized with the data obtained by the production line (the FML of the Lab) under analysis and, accordingly to the data collected by the ontology, it is possible to determine the quality of the realized product.
- *Fulfillment of Secondary Objective 4:* In the proposed solution a combination of product and process based approach is

utilized. In fact the proposed solution consists in determining the status of an asset, the drilling machine, following the data collected by the FML and then determining the quality of the product made accordingly to the status of the Asset and the state of the PCB, one of the components of the product, in function of what has been observed by the camera of the Camera Station. This choice was done since accordingly to [4] one of the two process can be more or less effective in function of the industrial context of application, for this reason the proposed tool do not impose a specific approach but it allows to adopt the way that best suits the specific context.

Besides the Research Contributions, it was possible to identify a series of shortcomings that led to the definition of some practical objectives that have been fulfilled by the solution found:

- The realized ontology is able to interpret the data coming from the servers of the FML through the use of a python code which puts the ontology in contact with a local database (InfluxDB) and also allows to use this data in order to perform the population of the ontology.
- Once created, the ontology allows the user to determine the quality of the product made by the line using the data provided by it and allows the user to identify and classify the characteristics of the product such as its components and their status or the production process which was used.

The solution of this thesis work has some limitations on the ontological modelling side as well as on the technological deployment side. As a matter of fact, the ORMA+ ontology, like the ORMA ontology [3], could not manage multiple 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 working step. From the technological deployment side, the Digital Twin obtained with this thesis work is a digital copy of the product which requires the presence of an operator to make decisions based on the results shown by the ontology, given the lack of the necessary instruments on the line to perform such operations. In a similar way, the Repair and Disassembly actions theorized in the validation of the ontology have been just introduced as proof of concept since in the FML line, as physical place, there is not the possibility to apply these actions.

Overall this thesis work paves the way to other future researches. The proposed solution can be enhanced introducing a system with the necessary instruments to fully exploit the potentialities of the ontology, or, as other option for future works, it is possible to introduce in the proposed solution the Zero Defect Manufacturing strategies now not considered, in order to make the solution more complete. Furthermore, it is possible to introduce other possible monitoring systems using the other data available in the industrial context within the proposed solution.

References

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