Zero Defect Manufacturing Strategies and Platform for Smart Factories of Industry 4.0

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Abstract. Within the context of market globalisation, the quality of products has become a key factor for success in manufacturing industry. The growing unpredictability of demand necessitates continuous adjustments in production targets. Addressing customer needs and customer satisfaction are the most important factors for successful businesses. Being consistent in meeting their needs, the existing manufacturing systems have to be adaptable while maximising the quality of their products. Guided by this challenge, in this paper we provide a holistic framework and ad-hoc strategies applicable both to new and existing manufacturing lines to achieve zero-defects in manufacturing via a novel ZDM platform that integrates state of the art ICT technologies, AI models and inspection tools which elevate manufacturing plants to a superior level of competitiveness and sustainability. The proposed approach and results in this article are based on the development and implementation in a large collaborative EU-funded H2020 research project entitled Z - Fact0r, i.e. Zero-defect manufacturing strategies towards on-line production management for European factories.

Keywords: Industry 4.0 · Zero - defect manufacturing · Big data · Smart factories · Sustainable manufacturing · Industrial production

1 Introduction

Nowadays, the efficiency and sustainability of the manufacturing processes of high-tech products depend on the introduction of Advanced Manufacturing Technologies in the production processes [1]. In particular, the development of metrology solutions for zero defect applications is considered as a robust technology able to provide a vast competitive advantage to manufacturing companies [2]. This trend is perfectly identified by "European Factories of the Future Research Association" (EFFRA) in the "Multi-Annual Roadmap for Factories of the Future" for 2014–2020 under the framework of the penetration of flexible and smart manufacturing technologies in the field of control and monitoring of the quality of manufacturing products [3].

Manufacturing enterprises are pushed to take "local" actions: thinking globally but acting and staying economically compatible within the local (regional and national) context. In order to achieve high precision manufacturing of complex products, there

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has to be a fundamental rethink on how to increase the accuracy of machines and improved controls [4]. The improvement should not only concern the individual machines as isolated islands but encompass the totality of production process as a system of interrelated elements that seek to maximise efficiency, productivity, customer satisfaction; whilst at the same time eliminate waste and excess inventory.

To meet the requirements mentioned above and aligned with the Industry 4.0 key objectives toward eco-factories of the future [5, 6], this study provides a holistic framework and a comprehensive set of integrated strategies encompassing the whole manufacturing line for addressing the issue of zero defect manufacturing in smart factories of industry 4.0. Doing so, the research aims at providing an answer as to what could be the proper strategies and associated technologies to effectively minimize product defects in manufacturing systems. A large collaborative EU-funded H2020 research project entitled Z - Fact0r [7] has been the main driver of the described approach and is designed for its validation. The project consortium is formed by 12 organisations across Europe including industrial pilot plants, academic institutions and technology providing companies.

To this end, novel strategies are designed in this research to be deployed at the field. The implementation of Z-strategies solutions leads to the achievement of zero defects in a multi-stage production line. The zero defect management system proposed in this study will be demonstrated in three use cases, covering different industry types (i.e. electronics, and hard metal), proving its universal applicability and the achievement of zero-defects in multi-stage productions of various types.

2 Strategies for Zero Defect Manufacturing

The innovative synergies between online data gathering systems, real-time simulation models, data-based models and the knowledge management system form the main strategies which eliminate the generation and propagation of defects. On that regard, the proposed solution comprises the introduction of five (5) multi-stage production-based strategies targeting (i) the early detection of the defect (Z - DETECT), (ii) the prediction of the defect generation (Z - PREDICT), (iii) the prevention of defect generation by recalibrating the production line (multi-stage), as well as defect propagation in later stages of the production (Z - PREVENT), (iv) the reworking/remanufacturing of the product, if this is possible, using additive and subtractive manufacturing techniques (Z - REPAIR) and (v) the management of the aforementioned strategies through event modelling, KPI (key performance indicators) monitoring and real-time decision support (Z- MANAGE). Accordingly, the focus is on part, machine and process level to monitor the status of the manufacturing process in real time, and new strategies based on real data are defined to detect and prevent the generation of errors and defects. In case an error occurs, instead of wasting the part, corrective actions are suggested based on correlations and decision support mechanism. Also manufacturing equipment, part and process status measurement analysis are adapted to provide the means for process validation. Each of the developed strategies are triggered based on detecting and assessing the impact of system level events that cause lower quality, generate defects, and increase the costs. The holistic approach utilizes all the acquired data from which a prediction is made with confidence levels above 95%. Figure 1 highlights synergies and interactions between the five Z - Fact0r strategies which are further described below:

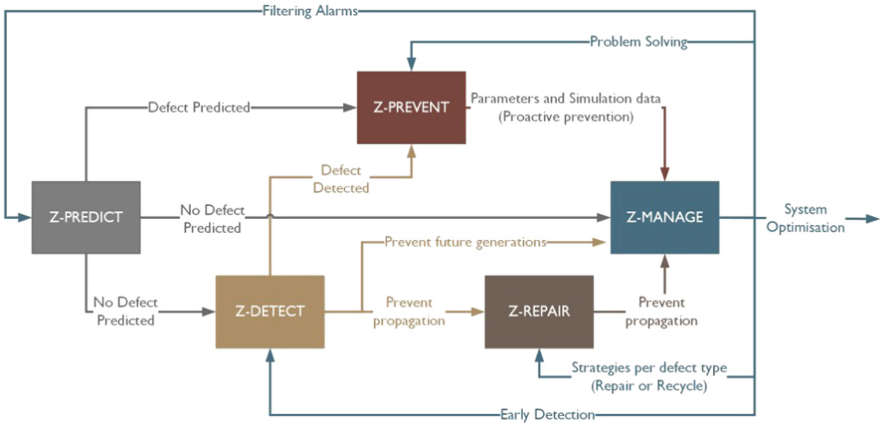

Fig. 1. Synergies and interactions between the five Z – Strategies

Z - PREDICT: The events detected from the physical layer of the system are engineered into high value data that will stipulate new and more accurate process models. Such an unbiased systems behaviour monitoring and analysis provides the basis for enriching the existing knowledge of the system (experience) learning new patterns, raising attention towards behaviour that cause operational and functional discrepancies (e.g. alarms) and the general trends in the shop-floor. The more the data pool is being increased the more precise (repeatability) and accurate the predictions will be. The estimations for the future states involve the whole production line, e.g. machine status after x number of operations and/or quality of the products for given set of parameters. The system can thus predict with high confidence the expected quality and customer satisfaction, allowing modifications to the parameters before the production of the products. In addition, it can operate in the reverse mode, i.e. insert a Customer Satisfaction Goal and control the parameters accordingly to achieve this target. The ability of the proposed zero defect management system to optimize the manufacturing processes according to certain/target quality levels and/or customer satisfaction is the key innovation to fulfil the industrial requirements.

Z - PREVENT: The prevention of defects strategy is based on the quality control and the inspection tools realized across the shop floor for condition monitoring of machinery and respective produced quality. The Z - PREDICT is predecessor of Z-PREVENT. The initial estimation of the future states and expected outcomes are taken into account and based on the simulation and modelling of the parameters. For each predicted defect, the responsible parameters are identified and flagged. The system adapts these parameters based on an initial estimation, which after the simulation are corrected recursively. The result of this process is to avoid the generation of defects based on each recorded event (defect, no-defect, low quality, high-quality) both from previous and current states. The system will demonstrate reduced false alarms by combining the future predictions.

Z - DETECT: This strategy is invoked when a defect is being generated after the adaptation of the parameters. In such a scenario, an alarm is being triggered to flag the parameters that resulted in a defect. By mapping the true reasons, the system is able to avoid having more generated defects by weighting the system model. Apart from the inspection of the product (from which the defect is being observed), the strategy involves more actions and processes to deal both with the generation of the detected defect, and its propagation to the next stages. Depending on the state that the defect was generated, the system will adapt its parameters to the previous successful state and plan to send the defected product either to downstream or upstream stage. The final decision on the actions is based on the Z - MANAGE strategy.

Z - REPAIR: Once a "repairable" defect is detected, a proper and customized repairing action must be deployed with the minimum time and effort, assuring the best productivity and production flow. In fact, a major challenge for an effective ZD manufacturing is related with the capability to automatically repair the occurred defects without perturbing the overall production flow. The proposed zero defect management system is based on a model-based, supervisory control solution that is able to interpret the inter-stage quality control measurements together with the monitoring of the process itself, in order to identify the defect sources and generate a proper and customized repairing action. Additive manufacturing in the form of inkjet or paste printing of various materials (metal, ceramic, and polymer resins) can successfully be used to fill a missing spot or correct a damaged part. Upon detection of the defected area, the printing head can deliver the patch material in solution or paste form. In the case of inkjet printing, defects as small as 20 μm can be patched. Post printing treatment of the delivered material include solvent evaporation (e.g. in the case of polymer patches), UV curing (e.g. in the case of epoxy resins) and low temperature laser sintering in the case of metal or ceramic nanoparticles, thermal curable resins or paste where a local reflow process is required.

Z - MANAGE: The overall supervision and optimization of the system is achieved after the execution of Z - MANAGE strategy. The defects are processed with Decision support system (DSS) tools and are interfaced with Manufacturing Execution Systems (MES). False positives and false negatives are clustered after the Z - DETECT strategy, which results into a good filtering of these false alarms. To achieve this, the previous acquired knowledge and incidents are also processed to fine tune the system's operation. Additionally, the production is optimized by better scheduling, taking into account the environmental impact of each process. The optimized scheduling and adaptability of the manufacturing improves the overall flexibility, placing a premium on the production rates, satisfying the demand, while preserving increased machinery availability. Since, the Knowledge Management system tunes the whole production according to certain quality levels and customer satisfaction, it is highly anticipated that the overall performance of the system suffices the increased needs of the customers. The strategy involves also the decision making in the event of a defect. The defect should be analysed via the Inspection system, from which the defect can be classified and categorized on its severity. In case of "repairable" defects the system decides for the following; (i) rework on spot, (ii) removal from the production line for further inspection and rework. If the defect is classified as "non-repairable" then the system decides whether the product will be (a) forwarded to upstream stages, or (b) considered as total failure where it will be recycled.

3 Proposed Zero Defect Management System

An efficient and effective zero defect management system should deal with the current trends for customisation and demand for zero defect manufacturing by introducing a holistic approach to not only achieve zero-defects but also maximise quality and performance. To do so, we employ five (5) strategies, namely Z - PREDICT, Z - PREVENT, Z - DETECT, Z - REPAIR and Z - MANAGE, all of which can be applied in the existing manufacturing plants with minimum interventions. Each of the strategies, as the name suggests, serves a different role which act synergistically with the others. The methodology relies on two inspection systems - one on the Work-Station level and one on the product level, as well as one online data gathering system and one online Defect Management system. In addition to the above, a Knowledge Management system provides intelligence and robustness to switch into the right strategy dynamically through the use of the three sub - systems. Figure 2 illustrates all the processes to achieve zero defect manufacturing from the four sub-systems and the output commands of each strategy.

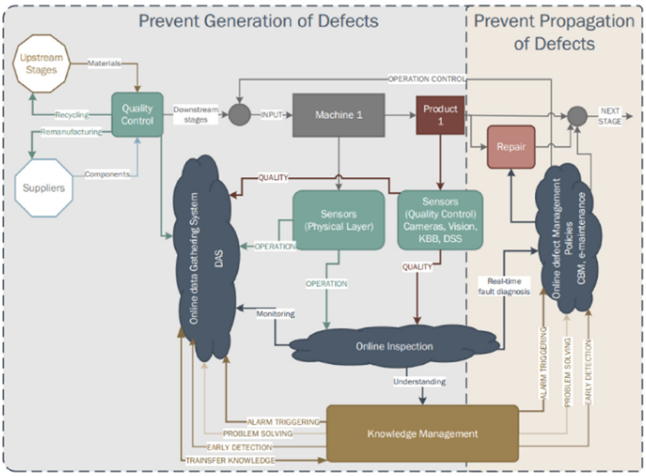

Fig. 2. Zero defect manufacturing system

Deployed Sub-systems

Work-Station Level: A series of sensors and actuators take readings for both the intrinsic and extrinsic machine's key performance parameters. The intrinsic parameters represent each factor that affects the work-station's behaviour on system level, such as structural health, degradation of components, energy consumption, production rate, temperature, etc. The extrinsic parameters involve factors that do affect the machine's performance but are not in the system level such as ambient conditions, temperature, humidity, operator's or system's inputs, etc. For each of the deployed use-cases there should be a different set of intrinsic and extrinsic parameters.

Product Level: Optical and visual sensors (lasers & cameras) monitor the quality of each product, according to the requirements for each use-case, based on the specific requirements of the parts from the use cases, it should be decided for each of the processes the areas to be inspected and the time available for such inspections. This frames the % of parts that are measured in each batch. The goal is to ensure that each product conforms to the pre-defined upper and lower acceptable quality limits. To this end, the repeatability is a critical indicator which is monitored using statistics. The goal of this approach is to categorise the products in quality classes, such as class A, class B, etc. All of the produced results are stored according to the quality inspection based on the requested quality, expected quality, and actual quality. The actions should then be aligned with the ISO 9001:2015 aiming at continual improvement to meet customer requirements and the industrial stakeholders.

Data Gathering: The data produced throughout the process along with the Inspection of the production line (Work- station & Quality) are logged into servers with time indexes. Wireless or cable transmission of data are achieved through a local area network. In order to avoid conflict and loss of data, each of the generated information is stored in the hard drives following a defined filing structure and naming system throughout all the stages.

Knowledge Management: This system receives input from all the rest acting as the "brain" of the zero defect management approach. The goal of this system is to provide feedback for all the processes executed in the production line. This system comprises an event modelling algorithm to identify the parameters from the overall production line which affect the Overall Performance Indicators (OPI) such as customer satisfaction, product quality, energy consumption, inventory control, and environmental impact. The decision support systems (DSS) and data management algorithms allow the evaluation of each performance and response to defects keeping historical data. The goal of this system is to optimise the overall manufacturing and the involved processes. To do so, the output of the knowledge management system is to provide alarms which will be filtered after the inherent learning process. Additionally, from the previous acquired knowledge early detection of defects are allowed with increased confidence levels. As a result, the proposed system is able to solve the problems arising in the production to maximise performance signalling strategies for handling the possible defects.

4 Zero Defect Manufacturing Platform Based on Z - Strategies

Manufacturing processes have to be environmental friendly and safe and deliver high quality products adapted to customer requirements, whilst minimising costs. The increasing interest in sustainable production places a premium on reducing material waste, re-works, rejects and stocks and has led to a demand for the development of zero-defect strategies at system level.

On that vein, the current trend in multi-stage manufacturing is towards more complex, distributed and faster evolving manufacturing facilities. To develop a zero-defect strategy to cope with increasing competition and sustainability related issues, plants should be designed and managed using best practices from emerging key enabling technologies. To that end, it is required to integrate a plethora of novel ICT technologies, state of the art algorithms and models, to support context awareness, inference conclusions, trend and root cause analysis, etc. to support online inspection, monitoring, and overall defect lifecycle management, towards zero-defect process operation and enhanced output quality. The final aim is to achieve production system configurations that profitably exploit the quality/productivity trade-off at system level whilst reducing complexity.

For that purpose, aligned with the Z - Strategies and the proposed zero defect management system concept explained earlier, a set of technologies and overall system architecture have been identified as a part of the proposed approach, following the method and procedures developed and proposed by May et al. [8].

The first high-level description to lead to the definition of the zero defect manufacturing platform consisted in identifying and classifying all components that can be called as the tools' landscape and logical architecture, i.e. conceptual view. Figure 3 presents this landscape by proposing a compact representation of the involved tools.

Based on the proposed approach and defined conceptual view of the system, in Z - Fact0r a novel zero defect manufacturing platform will be developed and demonstrated in three pilot plans proving its universal applicability for the achievement of zero defects in manufacturing. Therefore, the zero defect manufacturing platform will:

- Identify incoming defects and assure the best quality and the maximum production throughput;
- Reduce rejects and re-works by (a) identifying defects in parts caused by faulty machines, (b) by encompassing models and tools to support strategies for Predicting, Preventing, Detecting and Managing defects;
- Introduce autonomous diagnosis capabilities, including root cause analysis, (realized by the ES-DSS) aligned with both the production context (infrastructure, equipment) and the product (quality specifications and actual status);
- Integrate sensorial network with novel self-adjustment mechanisms to leverage semantic interconnection of sensors and online inspection tools, to manage, not only distributed data gathering from the shop floor, but also inter-stage communication and flow of production processes.

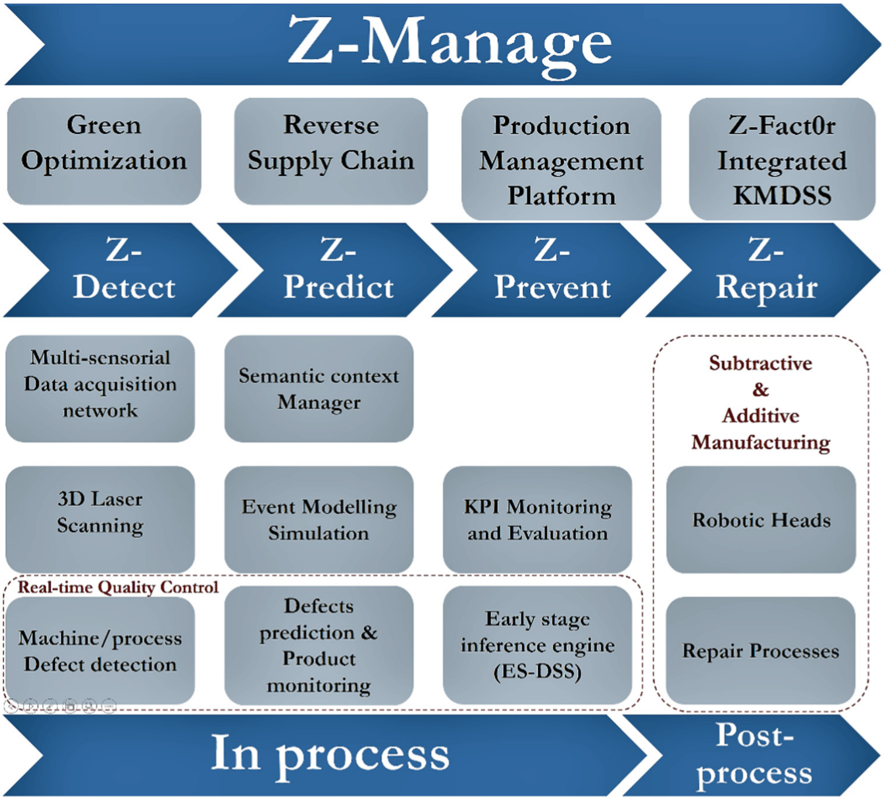

Fig. 3. Z - Fact0r tools' landscape

Following the development of the conceptual view, the required components have been highlighted in a preliminary architectural view, identifying services and dependencies within the Z - Fact0r platform. Later, new components were added in order to cover all the required functionalities of the resulting predictive maintenance platform.

Z - Fact0r functional viewpoint thus contains all the functions that the system should perform as well as the responsibilities and interfaces of the functional elements and the relationship between them. These functions are described using UML diagrams. Figure 4 shows the component diagram view of the overall Z - Fact0r architecture.

To sum up, the main components, their functionality, and their interactions are described in the functional view. Accordingly, the main components for Z - Fact0r architecture are:

- HMI & Sensor Network, which includes sensors, actuators, HMIs for humans to provide input to machines and thus the overall system, cameras, network infrastructure, legacy systems, etc.
- Shop-floor components which comprise semantic context manager, data acquisition and processing including 3D laser scanning, and Z - Fact0r repository.

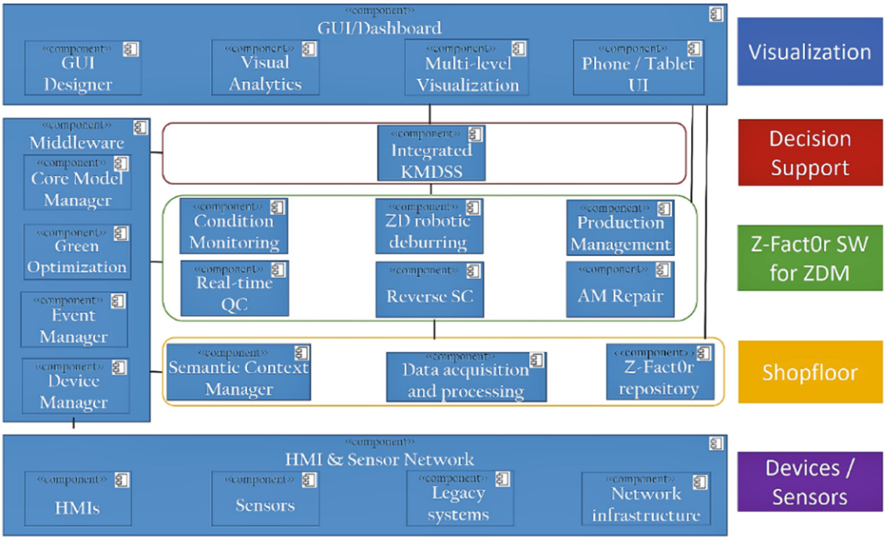

Fig. 4. Z - Fact0r system architecture

- Middleware including device manager, event manager, green optimizer, and core model manager.
- Z - Fact0r software modules for zero-defect management in manufacturing, which builds the service layer and includes Z - Fact0r specific tools such as real-time quality control, production management, reverse supply chain, zero-defect robotic deburring, and additive/subtractive manufacturing repair.
- Decision Support System (DSS) component, which will supervise and provide feedback for all the processes executed in the production line, evaluating performance parameters and responding to defects, keeping historical data.
- Besides, to facilitate the implementation of the five strategies, Z - Fact0r consortium has considered a policy to support a "reverse supply-chain" in the context of a multi-stage supply-chain attached to a multi-stage production. As a result, the defected products/parts detected in downstream stages (produced during a stage, or provided from suppliers in a particular stage) could be returned to upstream stages (internal or external supply-chain tiers) for remanufacturing or recycling.
- Finally, a visualization layer has been foreseen, which includes GUI/Dashboard designer, Visual Analytics Module, multi-level visualization component, and phone/tablet UI, etc.

In general, the idea of Z - Fact0r complete solution comes from the knowledge on the blackboard's architectural pattern that provides a computational framework for the design and implementation of systems that need to integrate large and diverse specialized components. This Z - Fact0r blackboard architectural pattern provides the essential communication elements (middleware) for sharing information among components. In this context, novel correlation of machine behaviour with the process performance and the produced quality provide a vital feedback to the control loop in manufacturing systems. Z - PREDICT strategy gives estimations for the future states involving the whole production line, e.g. machine status after x number of operations and/or quality of the products for given set of parameters. The system can then predict with high confidence the expected quality as well as the customer satisfaction. The simulation is able to insert desired values and to predict the outcomes, making the zero defect management system a ‘tailor-made’ instrument. Z - PREVENT strategy tunes the system based on historical, current, and future (predicted) data to fine-tune the system to preserve the quality levels inside the acceptable limits. Z - DETECT strategy is triggered in the event of a defect. The logged data both for machine and product level avoids the generation of future defects. In addition, based on the inspection data the system deals with the defects to stop its propagation. Z - REPAIR strategy allows reworking to take place optimally, reducing the direct rework costs, making the outputs acceptable based on the quality standards. Last, the Z - MANAGE strategy acts as the brain of the whole system, receiving all the data and analysing them. The result is filtered alarms, early detection of defects, solutions to generated problems, strategies for repairing (rework or recycling) which all lead to system optimization and zero defects manufacturing.

5 Conclusion

In this paper, we provided a holistic framework and ad-hoc strategies applicable both to new and existing manufacturing lines to achieve zero-defects manufacturing via a novel ZDM platform that integrates state of the art ICT technologies, AI models and inspection facilities which elevate manufacturing plants to a superior level of competitiveness and sustainability.

Addressing the changing Customer needs and achieving customer satisfaction in the current factories is a great challenge, which when met it’s translated to business success. The proposed ZDM system proposed in this study considers these external factors as Key parameters integrating them in the processing, allowing re-tuning of the manufacturing line in order to meet the desired targets at all times. The holistic framework envisages to consider all the multi-stage manufacturing line as a living organism (as a whole) identifying which parameter causes diversion from the initial targets and lead to defects and/or reduced sales. Hence, the ultimate goal of Z-Fact0r is to become a standard for all the factories of the future in order to achieve zero defects, minimised costs, increased quality and customer satisfaction, while being environmental friendly. Therefore, Z-Fact0r comprises a complete monitoring solution for every manufacturing process as a sustainable and viable system.

Future work will focus on implementing and validating the proposed approach on several use cases in different industries, demonstrating its ability to support major actors of the manufacturing sector to take advantage of the digital transformation.

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