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Resilience and Sustainability plants improvement through Maintenance 4.0: IoT, Digital Twin and CPS framework and implementation roadmap

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Abstract: The Fouth Industrial Revolution is the new innovative wave that touches any sector, bringing great innovation. As the benefits that Industry 4.0 can create are very high, it is mandatory to deeply investigate it and elaborate full applications. Digital technologies require to be faced with a correct pace, beginning with a small pilot, able to generate quick and valuable results. A domain in which Industry 4.0 can bring a great and positive effect is Maintenance, with predictive and prescriptive maintenance. In this research, it is analyzed how Internet of Things (IoT), Digital Twins (DT) and Cyber Physical System (CPS) can enhance maintenance and how they can be integrated to create the Maintenance 4.0 framework, with a clear focus on Resilience and environmental Sustainability, applied with a 6 steps roadmap based on the "starting small" authors' approach and initial assumption.

Keywords: Maintenance 4.0, predictive maintenance, prescriptive maintenance, Industrial Internet of Things, IIoT, Digital Twin, Cyber Physical System, CPS, Resilience, Sustainability.

1. INTRODUCTION

The consolidation of Industry 4.0 paradigm and the spread of digital technologies are the new trend of the Fourth Industrial Revolution (Samadhiya et al., 2023), bringing advantages in both private and public sector (Foresti et al., 2020), from increasing KPI to improve workers health (Porta et al., 2020) (Porta et al., 2021) to Supply Chain (Borelli et al., 2013). The possibility of applications is virtually unlimited (Çinar et al., 2020), however, the adoption rate of the 4.0 technologies is still partial and far from being fully achieved due to concerns about the new technologies. Managers need to clearly understand the potential benefit and the economic aspect to evaluate the cost-benefit and the return on investment (Stefanini et al., 2022). Industry 4.0 applications need thus to be designed and applied with a clear implementation roadmap and small cheap pilot projects, able to quickly show the return of the investment. "Starting small" is in fact a key point of Industry 4.0 and it is taken as the initial assumption by the authors. A little scalable system is less expensive than a big one, and then very appreciated by management, especially when it comes of crisis periods, like the current one, suffering for wars, like in Ukraine and Israel, and still weakened by recent Covid pandemic. The adoption of Industry 4.0 cannot be taken superficially (Chen et al., 2021). Pilots are then required and also very useful to learn about compatibility of systems and technologies, like RFID (Spano et al., 2014), across different levels of the business (Borelli et al., 2010).

A good starting point can be in the maintenance domain (Samadhiya et al., 2024). With this new amount of high-quality information provided by Industry 4.0, it is possible to increase the insight of plants and machines, with a consequent better maintenance (Zonta, et al., 2020), both predictive and prescriptive.

Increasing the quality of maintenance enhances the Resilience, meant as the ability to face disruption and return to the previous level or even higher than before (Pan, 2019), of the entire system (Lee et al., 2020), and the environmental Sustainability, reducing the impact on the environment (Frankó et al., 2022), a very current and important topic (Allahloh et al., 2023). The themes of Resilience and Sustainability are, with the human centricity, the main key points of Industry 5.0 (Psarommatis et al., 2023).

This paper aims to address the impact of Industry 4.0 on maintenance, by analyzing the adoption in this domain of Internet of Things (IoT), Digital Twins (DTs) and Cyber Physical System (CPS) for the creation of an innovative Maintenance 4.0 framework, based on the integration of these technologies, and presenting a 6 steps implementation roadmap following authors' "starting small" approach, with a clear focus on the resilience and the sustainability.

2. PROBLEM STATEMENT AND RESEARCH QUESTIONS

Industry 4.0 importance is undeniable and wide appliable (Foresti et al., 2020). However, the adoption is still incomplete due to the difficulties concerning the first projects. To face this problem, a study able to provide implementing tips is required to close the gap between potential and reality. Moreover, resilience and sustainability are very important topics, but yet not enough studied connected to Industry 4.0.

In order to better address the important problem described above, it has been focused on maintenance and translated into 3 research questions:

1. How can IoT, Digital Twins and CPS be implemented in the maintenance domain?
2. How can the 3 technologies studied above be integrated to create a full system for Maintenance 4.0?
3. What is the impact of Maintenance 4.0 on the Resilience and the Sustainability of companies?

The choice of these RQs has been made following a clear logic path aimed at innovation. Starting with the analysis of the

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single technologies, proceeding with the study of their integration to create Maintenance 4.0 framework, and concluding with the evaluation of the impact on resilience and sustainability.

3. METHODOLOGY

Aiming to the maximum quality of the novelty of this paper, a deep insight into the existing literature has been carried out by using the database Scopus. The used strings of keywords are: ("Maintenance" OR "failure detection" OR "PHM") AND ("CPS" OR "IIoT" OR "Digital Twin" OR "Industry 4.0" OR "IoT") AND ("Resilien*" OR "Sustainab*" OR "green sustainability" OR "resource intensity", OR "energy consumption" OR "emission reduction"). The choice of these keywords follows a clear logic path. The first, "Maintenance", is chosen in order to limit research to only maintenance domain. Then, the second string has been set to study the Industry 4.0 technologies connected to that field. Finally, the third string provides the focus con resilience and sustainability, as the 2 characteristics on which the authors want to study the effect of 4.0 implementation. A total amount of 1.111 paper has been found. To reduce this number, filters in cascade have been used. At first, for the first string, it has been used the filter "keywords". Thus, the first string has been searched only among the keywords of the articles. In this way, 401 papers have been found. Secondly, to evaluate the most recent trends and applications, the considered years have been the last 5, with a total of 301 records. Then, the subject areas of interest have been limited to "Computer science", "Engineering", "Business, management and accounting", and "Decision science", obtaining 271 papers. Finally, as objective filters, only the journal articles (103), excluding conference papers and book chapter, in English have been considered (102), of which 93 available to read. These 93 papers were carefully analyzed, removing those out of scope. The final sample was thus formed by 51 records. To this amount, other 19 papers known by authors have been added to furtherly increase the quality of the paper and state its novelty. For space reasons, only 31 articles out of 51 are listed. Once the existing literature has been carefully analyzed, the authors studied how IoT, DTs and CPS can enhance maintenance and how they can be integrated to create the conceptual framework of Maintenance 4.0. Finally, once it has been theorized, the impact on resilience and sustainability has been studied to provide viable information for potential implementers of Industry 4.0 in the domain of maintenance, especially as pilot project.

5. LITERATURE REVIEW

Advanced maintenance anticipates system degradation by identifying its causal factors, enabling their control or elimination before any significant deterioration in the component occurs (Chen et al., 2021). This is possible through IoT, DT and CPS Technologies (Fernandez et al., 2021) (Parri et al., 2021) (Lee et al., 2021). Moreover, effective maintenance is essential for businesses-owners of the equipment, as reducing costs of supervision, electricity (Bányai, 2021), remote control and diagnostic systems. In this context, sustainable development activities within a manufacturing should be integrated with the Industry 4.0 technologies (Patalas-Maliszewska and Łosyk, 2022) in order to revolutionize production (Wang et al., 2020), by making data available to stakeholders at many levels much faster (Frankó et al., 2022). Furthermore, integrating new technologies facilitates the collection of data from a company in real-time and processing them afterwards (El kihel et al., 2022) that can have impact on cost caused by reworking and scrappage lowering carbon emissions (Allahloh et al., 2023) and environmental pollution (Chen et al., 2022) (Samadhiya et al., 2023). IoT is a group of devices that enable objects to be visible and reachable through the Internet (Turner et al., 2022) applicable to different sectors (Fernandez et al., 2021), both private and public. Examples are: Industry, with the name of Industrial IoT (IIoT) (Mosca, 2023a) (Mosca, 2023b); Healthcare, named Internet of Medical Things (IoMT) (Mosca, 2023c) (Mosca, 2023d), combining different technologies, like RFID (Borelli et at., 2012). Therefore, IoT and IIoT offer a new level of connectivity across operations by linking the supply chain, production, and services, ensuring operational monitoring of machinery, and providing the foundation for higher-level tools (Turner et al., 2022). A DT is a dynamic, digital replica of a technical object in which you can compare real behavior and derired one. DT can be particularly effective within the context of sustainable production and maintenance (Rojek et al., 2021), also to holistically integrate analytics into its decision making (Konanahalli et al., 2022). Thus, many studies focus on this tool. Predictive maintenance models increasingly rely on data generated by DTs (Pinciroli et al., 2023) and their analysis, rather than on methods based on experience (Karapalidou et al., 2023). The fundamental concept behind employing DTs in the maintenance field is to study how the behavior of a unit deviates from an idealized behavior. However, several challenges have been encountered in industrial implementation, thus the development of more complex models than a DT of machinery is necessary, to ensure production flexibility and reliability (Samadhiya et al., 2024) (Stefanini et al., 2022). Therefore, is necessary to focus on predictive maintenance methodologies in Industry 4.0 (Hassan, et al., 2023) by predicting trends, behavior patterns and correlations through a combination of statistical and AI-based models, to anticipate failures and improve decision making for maintenance activities (Çinar et al., 2020). By integrating Industry 4.0 technologies into the maintenance process, in particular tools such as IIoT enabled by ML (Foresti et al., 2020) for the analysis of big data, it emerges that, in the case of maintenance, there are specific models for every type of need (Zonta, et al., 2020). Consequently, in an Industry 4.0 context, being able to anticipate a system breakdown based on the estimation of its degradation while proposing a time window for a maintenance intervention has become essential (Vrignat et al., 2022). CPS is a system that joins the physical world with the digital one, and it is based on IoT and DT (Parri et al., 2021). It enables the 2 worlds to cooperate, and it has access to both, with a constant comparison of the real environment and the simulated one across all levels of production (Lee et al., 2020). It can be applied in many sectors, and it is a concept which expresses the maximum potential of Industry 4.0. The integration of these technologies, which permits the analysis of real-time data, enhances sustainable operation and maintenance (Jiao et al., 2023), optimizing the power generation sector and scheduling routine maintenance (Balaji and Karthik, 2023) (Bányai and Bányai, 2022).

6. MAINTENANCE 4.0

6.1 IoT for Maintenance

In the domain of maintenance, IoT, especially IIoT, can provide great value, as confirmed by literature review (Foresti et al., 2020). Remote real-time monitoring enables decision makers to have better knowledge of imminent failure and take countermeasures almost instantly, especially with feedback control through actuators, who are also checked (Manuello Bertetto et al, 2013), to be set quickly and with precision, minimizing downtime and the related costs, with a better result than just historical data (Arena et al., 2022). In fact, only with a real-time data flow the result can be higher. This is the basis for predictive and prescriptive maintenance, that overcome faulty maintenance and scheduled maintenance, and take into consideration also special fault causes. All this new available knowledge can bring not only to savings in terms of costs, but also to in an increasingly Resilience and Sustainability:

- **Resilience**: keeping monitored the system in *real-time*, it is possible to take the correct countermeasures at the correct time, enabling a greater Resilience, as the system is fixed as soon as possible and then the impact of adverse events is mitigated, as confirmed in (Lee et al., 2020)
- **Sustainability**: IoT can be used to analyze the emissions of the lines, whose increase can be sign of maintenance need.

6.2 Digital Twin for Maintenance

Digital Twins have a lot of applications. Concerning maintenance, an online real-time simulation enables to compare the real and the desired behaviors, acting as soon as the value of a parameter deviates from the correct one. The economic advantage is double: important savings as extraordinary fault causes are detected and scheduled maintenance is overcome and substituted by predictive one. The possibility to simulate different situations, moreover, is particularly valuable in multi-product facilities, as different outputs mean different utilization of machines, and thus different times before failure. Detecting bottle necks and failure causes becomes a lot easier and maintenance can evolve into a real prescriptive. Faults are detected in advance through the simulation and advice for corrective maintenance is provided. This results in an improvement in operational efficiency and a reduction in unplanned plant downtime and consequent costs due to lost production, even on future ones. This technology increases both Resilience and Sustainability:

- **Resilience**: a very precise intervention, in both time and activity to be set, makes the system turns to its previous behavior in a shorter time, resulting in a better Resilience. Moreover, different scenarios can be simulated and studied, with many adverse events.
- **Sustainability**: the possibility to check and fix problems before they spread, increases the Sustainability, as less spare parts are required and the defects are lowered, with the consequent reworks.

6.3 Cyber Physical System (CPS) for Maintenance

Joining physical layer and digital one, CPS unites the advantage of IoT and DT. By collecting high quality data in real-time from IIoT and integrating them into the simulation, CPS can enhance the level of maintenance, making possible high quality predictive and prescriptive maintenance. Moreover, CPS can integrate data from different Digital Twins. In this way, the whole system can be enhanced in terms of efficiency. Bottlenecks can be better analyzed, a greater insight is extracted, both common and extraordinary fault causes are considered, and cost are reduced, while efficiency and effectiveness are enhanced. This new maintenance has great impact on both Resilience and Sustainability:

- **Resilience**: the view and the integration of different DTs provides new knowledge depth, as the complete system can be analyzed with all the correlations and causations. The resulting system is thus more robust and resilient.
- **Sustainability**: as it can be studied the entire system, it is possible to evaluate the overall emissions and maintenance activities are related with sustainability.

6.4 Maintenance 4.0 framework

As presented in the previous 3 chapters, IoT, DTs and CPS can have singularly taken a huge impact on maintenance, unlocking great value. What it is presented in this paper as innovation is the full integration of these 3 technologies to create the new paradigm presented in Fig. 1. It is the evolution of *predictive* and *prescriptive* maintenance into maintenance 4.0, which comprehends both and enhances them, overcoming their limitations and with a greater impact on Resilience and Sustainability.

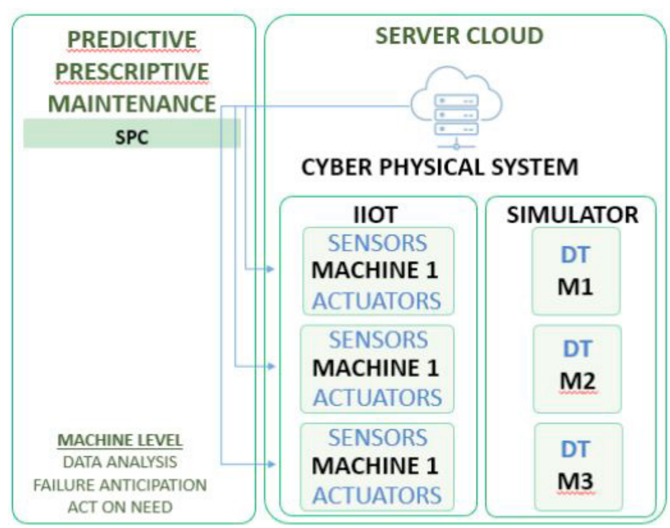

Fig. 1. Maintenance 4.0 framework.

This framework has been then articulated into a 6 steps roadmap, based on the initial assumption of "starting small":

1) **Data flow**: relevant parameters are chosen carefully, avoiding overloading, and reducing costs, by sharing knowledge among operators and maintaining team. This is also useful for the internal culture alignment to 4.0.
2) **Sensor choice**: the correct sensors must be chosen to have exactly what is needed, nothing more and nothing less.
3) **IIoT**: devices are mounted on machines and components.

4) **DTs:** it is created for each machine and line and the desired behavior is set in the simulation. IIoT and DTs are connected to each other, enabling the real-time data share.
5) **CPS:** DTs are integrated into the CPS, creating a full system, formed by physical and digital world. Statistical process control is applied with higher precision.
6) **Feedback controls**: based on deviation between desired and real conditions of the plants, their effect is predicted by the DTs. The CPS can send the information of the correction to implement to actuators through IIoT devices.

The benefits of this integration are many. The main are:

- **Cost savings**, due to less downtimes and spread of problems. The Total Cost of Ownership is also better computed (Roda et al., 2022).
- Increase in **efficiency** and **effectiveness**, with better quality of outputs, service level and customer satisfaction, like required in (Palacìn et al., 2021).
- Evidence based decision-making.

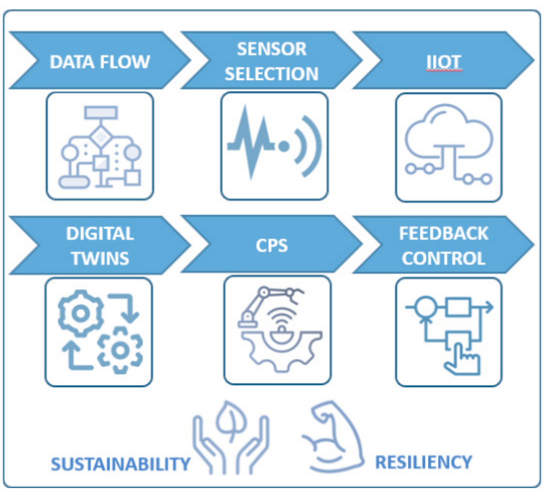

Fig 2. Maintenance 4.0 implementing Roadmap

These very simple steps aim to simplify the adoption of Industry 4.0, dividing it into steps easily followable also by smaller realities. Authors' approach to Industry 4.0 is in fact based on a "Starting small" one, to reduce the resistance to innovation, proving thus a clear human centric view, and the economic impact, by reducing risks. Finally, this adoption has a clear effect on resilience and sustainability of companies.

- **Resilience**: disruption is better faced, with the scenario and the online real-time simulation, and restoration to the normal conditions is in short time. Resilience is then the ability to restore the previous conditions and to improve after adverse events occurrence.
- **Sustainability**: all the emissions and consumptions are monitored, and the effects of internal policy and activities are evaluated. When components are not working as required by sustainability guidelines, maintaining teams can operate to fix the problem. Also the impact on the energy consumption is reduced, as the initial choice of data following this Roadmap reduce CPU usage.

The framework discussed in this section is meant to be created following the 6 steps path, in order to reduce the resistance to change and enable people to accept and take the maximum from the new technologies. This view in line with the human centric key point presented in (Psarommatis et al., 2023).

7. RESULT AND DISCUSSION

A first result is that more than 75% of the articles about this topic has been written since 2020, clear proof of the novelty and the very current interest of this work. Industry 4.0 is a very recent paradigm, started between 2010 and 2015 and that means that a lot of work is still to be done.

Secondly, analyzing carefully the 3 technologies, the different advantages in maintenance have been highlighted and the integration has been carefully evaluated.

Thirdly, an easy and linear 6 paths roadmap has been presented. Starting from data decision and proceeding to IIoT, DTs and CPS implementation, ending with automated feedback controls. This result is very important as it enables companies, also the smaller ones, to bring Industry 4.0 inside their realities with the least effort and the quickest returns.

Fourthly, it has been shown that resilience and sustainability are improved by the adoption of Industry 4.0, especially when more technologies are integrated. This further result is of great relevance, as it is a clear indication that the introduction of IIoT, DTs and CPS is one of the possible solutions to, on the one hand, increase resilience, a characteristic more and more studied and desired in any field, and, on the other hand, enhance sustainability, a fundamental topic due to the rapid climate change.

8. CONCLUSION

Adopting Industry 4.0 is a fundamental step any kind of company must take as soon as possible. However, although the advantages are undoubtedly high, costs and lack of knowledge about the implementation are hurdles that anyone have to face and solve somehow. IoT, Digital Twins and CPS have been studied and their value on maintenance is great, answering with great result RQ1, both with literature insight and authors' framework. The combination of these technologies, which follows RQ2, leads to the creation of Maintenance 4.0, a new trend of this domain, which combine *predictive* and *prescriptive* maintenance, meeting what expected by literature review (Chen et al., 2021) (Bányai, 2021). Finally, the answer to RQ3 was totally positive. In fact, Maintenance 4.0 provides a lot of benefits on both resilience and sustainability. Once again, respecting perfectly what highlighted by literature review (Patalas-Maliszewska and Łosyk, 2022). With this research, the problem statement has been faced and a solution for Industry 4.0 has been proposed.

9. FUTURE WORK AGENDA

The future works will focus on completing the roadmap for the 4.0 technologies adoption, including other innovations, evolving what developed in (Mosca, 2022a) (Mosca, 2022b). Resilience and sustainability in maintenance and other domains will be addressed, improving the already done works like (Mosca, 2022c). Finally, it will be faced the problem of SME (Small Medium Enterprises) implementation of 4.0.

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