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Editorial

Industry 4.0 Technologies for Sustainable Asset Life Cycle Management

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1. Introduction

Asset life cycle management is not a new concept for industries. Life cycle thinking means that people have a life cycle model in mind that affects the scope of their activities. A life cycle perspective for manufacturing assets is often mentioned in the literature regarding sustainability. This approach aims to understand and analyze individual stages of the asset life cycle, identify potential economic, social, and environmental risk factors and opportunities at each stage, and create possibilities to take advantage of these opportunities and reduce potential risks. In the Industry 4.0 era, manufacturers can monitor assets and make smart decisions in each phase of their life cycle through real-time communication and cooperation with humans, machines, sensors, etc. These technologies can support all stages of ALC through various emergent communication, information, and intelligence technologies. Technologies such as digital twin (DT), Internet of Things (IoT), cyber-physical systems (CPS) and their respective specialization to industry, the industrial Internet of Things (IIoT), and cyber-physical production system (CPPS), are considered in this Special Issue to increase the effectiveness of asset life cycle management (ALCM).

ALCM in manufacturing is increasingly adopting Industry 4.0 technologies for achieving sustainability goals. "Asset" refers to any piece of property owned by a person or a firm. The asset life cycle comprises everything that occurs from the identification of the need for the asset to its disposal. Traditionally, asset management has been identified as "a strategic, integrated set of comprehensive processes (financial, management, engineering, operating, and maintenance) to improve lifetime effectiveness, utilization and return from physical assets (production and operating equipment and structures)" Typically, asset management approaches focus primarily on cost minimization. However, in the current industrial setup, a strong positive correlation exists between environmental, social, and governance (ESG) ratings and the return on assets. The idea that organizations can achieve long-term benefits by focusing on sustainable development has motivated manufacturing firms to adopt Industry 4.0 technologies for ALCM. Asset-related decision-making holds the utmost importance in ALCM.

This Special Issue presents the papers in the five thematic areas related to:

- Implementing the sustainable development concept;
- Asset life cycle management for the sustainable industry;
- Trends in adopting industry 4.0 for asset life cycle management for sustainability;
- State estimation and remaining useful life prediction;
- The influence of material and manufacturing parameters on the properties of product.

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2. Implementing Sustainable Development Concept

For companies, sustainable development generally represents a long-term business orientation towards social, economic and environmental well-being. The concept has gained momentum among researchers partly due to the necessity of finding a modern approach to business development that does not deprive the next generation of the opportunity to meet its own needs. The literature indicates that sustainability practices may be particularly important to family-owned and -managed businesses due to various factors, most prominently the inclination to pass the business to the next generation and the company's long-term business orientation. Most research on family business sustainability has been based on a different scientific approach (e.g., qualitative or quantitative analyses or investigating only selected dimensions of TBL), considering different determinants of such activities (e.g., internal or external).

In paper [1], based on a sample of 333 Polish family firms, three groups of businesses were isolated (via k-means clustering) on the basis of low, medium and high deployment of pro-sustainability initiatives. This paper aims to investigate whether family firms demonstrating divergent levels of sustainable development express between-group differences. Measuring diversity using ANOVA with post hoc testing produced results associating business growth and higher levels of family involvement (e.g., via increased participation of family members from different generations in firm management) with the increased absorption of sustainable solutions and actions. These findings support notions from social identity theory, suggesting that groups significantly shape the individual identities of their members. This means that family members inclined to implement sustainable development initiatives are likely to stimulate each other to introduce particular solutions and actions in praxis [1].

The results of this paper confirm that Polish family businesses represent divergent levels of implementation of sustainable development solutions and actions. By considering 30 detailed aspects of social, environmental and economic pillars of sustainable development, participating family businesses were divided into three separate groups using k-means clustering. The first cluster of family businesses labelled "sustainable development laggards", included family firms implementing limited "passive" pro-sustainability solutions. This group featured the lowest level of engagement of family members in operating the business, and businesses were most likely to be managed by the founding generation. Finally, this cluster featured the smallest family firms (measured by the number of employees). The second cluster was labelled "non-formal sustainable development followers" and comprised family firms that had clearly implemented several pro-sustainable development solutions and actions. However, these businesses focused on aspects that could be implemented without external support, consultancy or formal confirmation. Nonetheless, family members were more engaged in the operations of these businesses, and younger generations were more involved in management. This cluster was also bigger than the first one. The highest level of implementation of pro-sustainable development solutions and actions was observed in the third cluster, labelled "sustainable development trailblazers". These businesses demonstrated insufficiency with regard to only a few aspects of sustainable development and were distinguished by the noticeably more substantial involvement of family members in business operations, the employment of later generations of the family in the managerial body and the larger size of the business.

Considering these findings, two main conclusions can be drawn in reference to management and practice. Firstly, more involvement of family members, both generally and as c-suite members, is aligned with the pro-sustainable orientation of family businesses. Secondly, particular pro-sustainable solutions are more or less suitable for a given business entity. Hence, policymakers or other groups of stakeholders that are interested in the implementation of various pro-sustainable solutions should adjust their formal and administrative requirements, taking into consideration both the real possibilities of businesses and their praxis needs related to the given sector of the economy they operate in.

Although this study features several limitations, it nevertheless presents opportunities for future research. The first limitation concerns the sampling process. Using a purposive sampling of Polish businesses that define themselves as "family firms" or that have declared a family share of equity capital above 50% limits the capacity to generalize the findings to family firms in other countries or family firms defined using another approach. To expand on these findings, similar studies should be conducted that use the same or similar methods to consider other samples.

Additionally, considering the sampling approach, it could be suggested that the results can be verified using completely random samples or using public statistics data to draw conclusions for the general population of family businesses. It also could be verified whether business size measured by other factors than employment, e.g., turnover or total assets, would confirm our finding related to these parameters. Moreover, this approach could prove whether the observations would differ if other family enterprise characteristics were considered. For example, it could be interesting to investigate whether family businesses in different sectors, which are publicly listed or not publicly listed or that represent various levels of internationalization, differ in terms of their engagement in pro-sustainable development solutions [1].

3. Asset Life Cycle Management for the Sustainable Industry

Considering the competitiveness of the global market, businesses must create data-oriented interactions to satisfy sustainability, which plays a relevant role in all phases of asset life cycle management. In the early phases of a product's development, several issues need to be addressed, including the product's design, manufacture, usage, disposal, and, respectively, its impact on society. Each of these stages has its own specific sustainability considerations and measurements. As an area of interest in digital transformation, from manufacturing to service and operations, the Fourth Industrial Revolution (Industry 4.0) presents the promise of enhanced flexibility, higher quality, and improved productivity [2].

Every physical asset needs a digital representation conducive to fully realizing the potential of Industry 4.0. To tackle difficult business problems, mirroring digital representations of actual assets can be quite valuable. One of the most desired qualities in the age of Industry 4.0 is, hence, the ability to deliver distinctive characteristics at scale. The fast advancement of communication and information technology has made it possible for digitalization to change how business is conducted along industrial value chains. Another term for this procedure is "Industry 4.0", or "The Fourth Industrial Revolution". The goals include highly customized and optimized manufacturing, as well as enhanced automation and adaptability. The industrial sector is already moving toward more sustainable practices by suggesting a number of strategies to improve the effectiveness of these environmentally friendly activities. The digital twin (DT) is one of the most promising enabling technologies for achieving these Industry 4.0 ambitions. Having a two-way dynamic mapping between a physical thing and its digital model, which has a structure of linked parts and meta-information, a DT is a digital representation of a physical entity [2].

In paper [2], the authors intended to shed light on the state of the art of DT case studies, focusing on concept, design, and development. The DT reference architecture model in Industry 4.0 and the value-life-cycle-management-enabled DT are also discussed, and a proposition of a DT multi-layered architecture framework for the mining industry is explained to inspire future case studies.

Driven by the rising demand for individualized and customized products, production is becoming increasingly complicated in terms of structure. Impacting all of the product life cycle phases, digitization is the main key to a transformation process that can lead to plenty of opportunities. It is empowering to introduce many engineering and management applications such as the DT. The current research aims to take full advantage of DT capabilities in response to the challenges faced in the mining industry. The goal behind this paper is to propose a generic DT architecture framework for the sustainable mining industry by adopting the reference architecture model in Industry 4.0 (RAMI 4.0) and enabling asset life cycle management by discussing the outcomes and potentialities of the use of DT technology. This framework establishes a collaborative environment that joins the two sides of the cyber-physical system, integrating the four services impacted: engineering, production, process and operation, and marketing and go-to-market.

Motivated by the benefits and opportunities enabled by using the DT approach, the goal now is to design a proof of concept of this framework in future work by developing an industrial case study of DT that facilitates the achievement of a sustainable mine, considering the asset life cycle management mirror and assuring the simulation and test of the process consistency over the life cycle phases [2].

4. State Estimation and Remaining Useful Life Prediction

Urban rail transit (URT) systems have a plethora of advantages, such as large passenger volume, low pollution emission, fast operation speed and safe and punctual operation. They constitute key infrastructure components that are able to support urban economic and social development within societies. URTs serve as the main ways for optimizing a city's functional layout, meeting people's travel needs, alleviating urban traffic congestion and promoting economic and social development. The traction motor is the core equipment of URT, and its electrical and mechanical properties are directly related to the efficiency and reliability of the whole system. The permanent magnet synchronous traction motor (PMSTM) is a feasible option for URT traction motors in light of its small size, high efficiency, low moment of inertia and fast dynamic influence [3].

A PMSTM can operate for extended periods of time under harsh working conditions, including high speeds, large loads, strong vibrations and severe noise, and its working state is associated with the safe operation of the entire URT. If the PMSTM fails, it will cause serious economic losses and casualties. It is essential to estimate the current health state and predict the remaining useful life (RUL) for PMSTMs. Directly obtaining the internal representation of a PMSTM is known to be difficult, and PMSTMs have long service lives. In order to address these drawbacks, in paper [3], a combination of SIR (sample importance resampling) and the HSMM-based state estimation and RUL prediction method is introduced with the multi-parameter fusion health index (MFHI) as the performance indicator. The proposed method's advantages over the conventional HSMM method were verified through simulation research and examples. The results show that the proposed state estimation method has small error distribution results, and the RUL prediction method can obtain accurate results. The findings of this study demonstrate that the proposed method may serve as a new and effective technique to estimate a PMSTM's health state and RUL. The correlations between the selected feature parameters were reduced using PCA (principle component analysis), and the MFHI was constructed through the corresponding weight assignment and fusion. HSMM training was then performed to describe the relationship between the internal state and observation sequence of the PMSTM, after which an overall performance degradation model was established. The observation sequence of the hidden state was observed to be directly recursive from the previous state through SIR, demonstrating the recursive optimal estimation of the internal state while realizing RUL estimation. By conducting simulation experiments, the state estimation and RUL prediction were performed by taking six groups of data as examples in order to verify the effectiveness of the algorithm. Additionally, compared with the conventional HSMM method, the results signify that the proposed method can generate more accurate predictions. In general, compared to other published methods, the method proposed in this paper was less computationally intensive and possessed more accurate computational results [3].

Future work might focus on finding more suitable methods to obtain observation sequences. Additionally, the authors are planning tests based on the proposed model.

5. Trends in Adopting Industry 4.0 for Asset Life Cycle Management for Sustainability

With the potential of Industry 4.0 technologies to enable sustainable manufacturing, asset life cycle management (ALCM) has been gaining increasing attention in recent years.

The authors of the paper [4] performed a keyword co-occurrence network (KCN) analysis of keywords in 3896 scientific articles related to Industry 4.0 as applied to ALCM for sustainability. These articles were published during the period of 2002 to 2021. The analysis reveals the evolution of knowledge structure over the past 20 years and the current and expected trends in the literature. The statistical analysis of network characteristics provides insights into trends in ALCM research (e.g., big data, artificial intelligence, IoT and cloud computing) over time. Traditional literature reviews discuss methodologies and experimental findings. In contrast, KCN provides a macro-level understanding of the evolution of the knowledge structure and knowledge components to inform researchers about the declining and emerging research topics in the literature [4].

In paper [4], the authors map high-frequency ALCM keywords to nine pillars of Industry 4.0: advanced simulation, system integration, autonomous robots, augmented reality, additive manufacturing, Internet of Things (IoT), big data, cloud computing and cybersecurity. The popularity of each pillar provides insights into future research directions. Results depict that, currently, the top three most popular pillars in sustainable ALCM research are big data, IoT and cloud computing. The KCN-based review and analysis results presented in this paper can serve as a road map for conducting a rigorous systematic review of the literature on Industry 4.0 technologies for ALCM [4].

Although this analysis uses only keywords to build the KCN and is as objective as possible, it may still have a bias as the authors might have failed to identify vital terms as keywords. Due to the limitations of the natural language processing methods, some distorted, irrelevant, and redundant keywords might have made their way into the final keyword list used for building KCNs. However, the effect of such noise in the keyword list is not likely to alter the observations made in this work. The KCN-based approach is otherwise very effective in reviewing the knowledge structure and research trends macroscopically. Future work could include extracting keywords from the articles' titles to make the knowledge coverage more comprehensive [4].

6. The Influence of Material and Manufacturing Parameters on the Properties of Product

Inspired by the increasing global concern about the environmental impact of the intensive use of polymer products, the incorporation of natural-based materials into polymer composites has been investigated in recent decades. The advantages of using biomaterials as part of composite materials are availability, recyclability, renewability and ease of processing, which allow for a partial or total substitution of petroleum-based products. Common fillers used for the production of natural-based polymer composites include materials from plant, animal and mineral sources [5].

Cork is a wood material obtained from the harvesting of Quercus suber L. trees, which are most common in the regions around the western Mediterranean Sea. The most recognized application of cork is in the manufacture of stoppers for the wine industry. Surplus from harvest and stoppers production can be introduced in the manufacturing of several composite materials, including agglomerated cork and cork–plastic composites (CPC). Cork–rubber composites are an example of cork composite materials, and consist of a rubber matrix filled with cork granules. These materials can be applied as bearing pads for vibration and acoustic isolation in the construction and industry sectors. Similar to other elastomeric products used for vibration isolation, a cork–rubber composite pad must be able to support the weight of the structure to be isolated and prevent or reduce the transmission of vibrations [5].

In paper [5], the addition of cork to a natural rubber compound and the vulcanization parameters were studied in terms of their influence on the properties of cork–rubber materials. The characterization of different compounds was carried out and included in the determination of mechanical properties related to the application of cork–rubber composites as vibration isolation pads, such as static and dynamic behavior under compressive loading. Statistical methods, such as ANOVA and regression analysis, were used in this study. The results showed that the introduction of cork as an additional filler in the studied rubber compound increased its hardness and static stiffness while maintaining a similar dynamic behavior to the base rubber compound when subjected to compressive loading. In addition, it was found that increasing the amount and granulometry of cork and lowering vulcanization temperatures resulted in stiffer vulcanizates. Materials with higher cork granule contents were found to be affected in their final properties by molding pressure. A study involving the use of linear regression models as a tool to predict or optimize properties related to vibration isolation applications was also developed.

Based on statistical methods, the effect of some variables related to the manufacturing of cork–rubber composites used for vibration isolation was analyzed. The study focuses mainly on the introduction of cork granules as an additional filler on a natural rubber matrix and the influence of the vulcanization process parameters on its properties.

The results showed that the addition of cork granules increased the mechanical properties of the rubber compounds, such as hardness and static stiffness. The addition of cork to a rubber compound has demonstrated a different dynamic behavior from other rubber compounds with various fillers. Generally, an increase in dynamic stiffness is observed in rubber due to the increase in the filler quantity. For cork–rubber composites, the results obtained demonstrate that the addition of cork was able to reduce or maintain the same values of the ratio between dynamic and static stiffness observed in a compound without cork granules when subjected to low compressive loads [5].

The effect of cork quantity and granule size on composite properties, such as hardness, stiffness, tensile and tear strength, and elongation at break and rebound, was revealed to be analogous to what was reported in other studies involving the introduction of a natural-based filler on an elastomer matrix.

The variation of the vulcanization temperature of some compounds was revealed to have a significant effect on the properties of the final product, while the pressure level proved to be a significant variable in the manufacturing of composites with higher contents of cork granules. The tendency regarding vulcanization temperature is similar to other rubber compounds; the application of higher temperatures corresponds to a decrease in properties, such as hardness and stress, at 10% strain. A linear trend regarding natural frequency was not so clear. Regarding the pressure level, more studies must be conducted to understand its influence on the mechanical properties of cork–rubber compounds, also considering the effect of variables related to cork granules [5].

The regression models were determined to be able to provide predictions about the behavior of cork–rubber composites under static and dynamic compressive loading, according to the quantity of the higher granulometry cork particles incorporated in the compound. For static behavior, the obtained coefficient of determination (R2) was below 45%, indicating a low prediction capacity. More data must be collected, and the existence of more influential variables should be examined in order to achieve a good prediction model for cork–rubber compounds. However, the developed model to predict the ratio between dynamic and apparent compression modulus according to the stress imposed and cork quantity resulted in a useful tool for a product's improvement with an R2 value above 90% [5].

7. Conclusions

Organizations have started recognizing that a strategic approach to asset management has become a source of sustainable competitive advantages and long-term survival in a turbulent environment. Asset management involves balancing costs, opportunities and risks against the desired performance of assets in order to achieve organizational objectives. It also comprises different stages of the asset life cycle. Physical assets, such as machinery, utilities, production lines and equipment, play indispensable roles in manufacturing, need to perform reliably, safely and economically and, according to life cycle thinking, contribute to a more sustainable production system. Life cycle thinking means that people have a life cycle model in mind that affects the scope of their activities. The goal of this approach is to understand and analyze the individual stages of the life cycle, identify potential economic, social and environmental risk factors and opportunities at each stage and foster an environment where these opportunities can be taken advantage of and the potential risks can be reduced.

Industry 4.0 technologies, such as digital twin (DT), Internet of Things (IoT), cyber-physical systems (CPS) and their respective specialization to industry, industrial Internet of Things (IIoT), and cyber-physical production systems (CPPS) can support all stages of assets' life cycle through various emergent communication, information and intelligence technologies. By using these technologies, manufacturers can monitor assets and make smart decisions in each phase of their life cycle through real-time communication and cooperation with humans, machines, sensors, etc. Under the promotion of smart enabling technologies, the data and knowledge share among various life cycle management sectors can be effectively facilitated, and more reasonable and precise decision-making of life cycle management can be achieved.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Domańska, A.; Więcek-Janka, E.; Zajkowski, R. Implementing Sustainable Development Concept: A Typology of Family Firms in Poland. *Sustainability* **2022**, *14*, 4302. [CrossRef]
2. El Bazi, N.; Mabrouki, M.; Laayati, O.; Ouhabi, N.; El Hadraoui, H.; Hammouch, F.-E.; Chebak, A. Generic Multi-Layered Digital-Twin-Framework-Enabled Asset Lifecycle Management for the Sustainable Mining Industry. *Sustainability* **2023**, *15*, 3470. [CrossRef]
3. Tian, G.; Wang, S.; Shi, J.; Qiao, Y. State Estimation and Remaining Useful Life Prediction of PMSTM Based on a Combination of SIR and HSMM. *Sustainability* **2022**, *14*, 16810. [CrossRef]
4. Weerasekara, S.; Lu, Z.; Ozek, B.; Isaacs, J.; Kamarthi, S. Trends in Adopting Industry 4.0 for Asset Life Cycle Management for Sustainability: A Keyword Co-Occurrence Network Review and Analysis. *Sustainability* **2022**, *14*, 12233. [CrossRef]
5. Lopes, H.; Silva, S.P.; Carvalho, J.P.; Machado, J. The Influence of Cork and Manufacturing Parameters on the Properties of Cork–Rubber Composites for Vibration Isolation Applications. *Sustainability* **2021**, *13*, 11240. [CrossRef]