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Using technology management to guide the journey to Reliability 4.0 in the manufacturing industry: A South African context using a case study of a Food and Beverage company

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An effective asset care strategy is considered a knowledge asset for manufacturing organizations. This knowledge asset can be exploited to achieve the financial and operational goals of an organization by reducing process variability and enabling a synchronous supply chain. Industry 4.0 has caused the technology landscape of asset-intensive organizations to evolve. However, there is a chasm in the body of knowledge that relates asset care systems to Industry 4.0 technologies and the subsequent opportunities to leverage asset reliability results. Reliability 4.0 is the intended output of a Maintenance 4.0 system, i.e., maintenance-related activities derived from applying Industry 4.0 technologies. A systems-thinking approach was applied to analyse the current asset care systems within a prominent food and beverage manufacturing company. The output of this process was a conceptual framework that applies technology management tools to support the development of an asset care strategy. The key characteristics of Industry 4.0, as well as data and process integration, are highlighted. This framework shows how internal and external factors should be considered to create an asset care roadmap to guide an organization's journey to Reliability 4.0.

Keywords: Reliability 4.0, Maintenance 4.0, Asset Care Strategy, Asset Care Roadmap, Industry 4.0.

1. Introduction

The term Industry 4.0 is used to refer to a group of interconnected technologies that generate vast amounts of data. This data aims to improve the information between the realms of physical- and cyber-space. Factories that combine digital technologies to gain resource productivity are called 'smart factories'. These factories are often asset-intensive and driven by intelligent data obtained from interconnected cyber-physical systems (CPS).

Manufacturing organizations develop asset care systems to prolong the useful life of their equipment. These systems guide and direct when and how assets are maintained. Technologically advanced equipment implies that a correspondingly advanced asset care system would be required to sustain these levels of associated productivity. Maintenance execution is a key activity of this system. Digitized manufacturing systems, however, imply access to vast amounts of real-time data. Large amounts of historical data pertaining to degradation patterns infer the possibility of predictive algorithms. These algorithms would prove invaluable when applied to an asset care strategy. Thus, Industry 4.0 technologies can provide an effective input into the process of asset care.

The progression of digitized manufacturing systems creates the need for asset care strategies to anticipate the disruptiveness of technology advancements by planning appropriately for this eventuality. Technologically advanced equipment requires an asset care system that is cognizant of the systemic internal and external factors that would potentially influence it. Bokrantz et al. (2017:155) state that there is an "apparent gap regarding the future of maintenance organizations". Bokrantz et al. (2017) propose that this gap manifests from the degree of uncertainty surrounding the technology that exists within the realm of digitized manufacturing.

Current asset care systems in South Africa are built around lean methodology and include at best, an enterprise resource planning (ERP) system to support storage, scheduling, and materials management (Ardito et al., 2019). There is very little research on how to integrate technology successfully within an organization's asset care strategy. The concept of viewing asset care as a knowledge asset is also novel in that many organizations do not consider this tool as a potential source of competitive advantage. An asset care strategy should consist of medium- to long-term goals. Therefore, an asset care roadmap should demonstrate how the asset care system of an organization should evolve.

The objective of this research was to develop an integrative framework that can be used by organizations to support the development of a strategic roadmap to guide an asset care system and achieve Reliability 4.0.

Given the research objective above, the following questions were posed:

- RQ1: How will asset care systems evolve to achieve Reliability 4.0?
- RQ2: How can technology roadmaps be used to guide the journey to Reliability 4.0?

2. Literature Review or Theoretical Framework

While there is much literature that postulates the potential impact of Industry 4.0 on manufacturing industries, this knowledge focuses on the technical aspects of these technologies. The corpus of knowledge that exists on digitized manufacturing relates to the expectations of technology and its implications for productivity. For example, highly automated factories are seen as an enabler of streamlined innovation processes and a productivity driver (Bokrantz et al., 2017). However, there is little literature that provides guidance on how asset care systems can support these technologies.

Digitized manufacturing environments differ from traditional automated systems in that the interconnectivity of equipment creates holistic patterns of information that enable more cognitive decision responses. Organizations are, therefore unclear about how to map out a path that balances operational requirements with the benefits that digital transformation is expected to offer (Hanley et al., 2018).

2.1 *Asset Care vs Maintenance Strategy*

In the literature, the terms 'asset care strategy' and 'maintenance management' or 'maintenance strategy' are often used synonymously. Coleman et al. (2017) considers maintenance strategy and processes to be the core elements of strategy development for maintenance organisations. However, having an asset care strategy in industry refers to the entire system as well as the activities that are needed to create machine reliability. It focuses on maintenance as a sub-activity that is integrated with production activities.

Developing an asset care strategy begins with understanding the level of maturity of an organization's maintenance practices. A good asset care strategy should also interface with environmental, health, and safety requirements. Maintenance execution should not be performed with just the up-time of machines in mind. Regulatory and ethical considerations should also feature in how these activities are performed. Therefore, an asset care strategy guides how maintenance activities are performed by outlining the goals and measures that should be followed (Brown and Sondalini, 2013).

2.2 *Reliability 4.0*

Machine reliability is the desired output of an asset care system. There have been no detailed studies that consider what reliability means in the context of Industry 4.0 technologies. The literature indicates a strong focus on traditional asset care systems and on the effectiveness of these systems. It also postulates and predicts that Industry 4.0 can improve productivity without specific guidelines on how to achieve the same. Tjahjono, Esplugues, Ares and Pelaez (2017) expand on the concept of a smart factory, arguing that it is a factory that can function autonomously by anticipating the needs of the supply chain that it operates within. This interconnectedness resonates with the characteristics of Industry 4.0, which is built on the concept of the IoT. Tjahjono et al. (2017) further propose that the advent of Industry 4.0 requires "collaboration" between strategic partners and functions to create "transparency". Therefore, to plan, warehouse, and distribute a product effectively and efficiently, it must be consistently available in the right quantity and quality. In other words, manufacturing operations are required to manage these aspects operationally with agility and responsiveness (Schumacher, Erol and Sihn, 2016).

While the concepts of maintenance and reliability are often used interchangeably, these terms do not mean the same thing. Ferreira et al. (2017:1) state that "the reliability and safety of industrial machines depend on their timely maintenance." Bengtsson and Lundström (2018:118) agree with this principle by stating that "maintenance is becoming even more important in serving the industry with safe, environmentally friendly, and available production systems that produce high-quality parts."

In summary, maintenance remains the activity that is performed to sustain optimum production levels by extending the lifecycle of the asset. At the same time, reliability is the output that enables the supply chain to function as an intra-organizational network and service the customer. Maintenance drives reliability, which in turn results in consistent manufacturing performance. Maintenance 4.0 refers to a system that employs embedded sensors, CPS, deep learning, and artificial intelligence to create a system capable of predicting future failures. The output of this system is Reliability 4.0.

For this research, the following definition for Reliability 4.0 was proposed:

Reliability 4.0 is the predictability of manufacturing outputs created by a manufacturing organization's maintenance and asset care systems as a direct result of its ability to leverage Industry 4.0 technologies. Maintenance 4.0 drives Reliability 4.0 as the system interacts with other factors (e.g., skills and technology).

This definition was proposed as no such definition has been encountered during the literature review.

2.3 *Technology Road mapping*

Technology road mapping refers to a technique that is used to provide a visual map of the technological evolution that supports long-term strategic objectives (Phaal et al., 2004). Phaal et al. (2004) propose that the road mapping technique could be used as a survival tool by virtue of the fact that it creates a focused approach that enables the processes of technology selection. Road mapping is considered to be a strategic technique that is both flexible and adaptable (Carvalho, Fleury and Lopes, 2013). The tool appears to be simple to use and can evolve into a rather tedious and time-consuming activity. Road mapping has been noted to be useful in attempting to eliminate knowledge gaps and support the decision-making and strategy development of organizations (Carvalho et al., 2013). A good technology roadmap should show the key layers that connect the various elements that drive business strategy. The most important feature of the roadmap is the progression of time; it represents the pathway followed to reach the end state (i.e., there is a 'bigger picture' mindset). An asset care roadmap is a type of roadmap that is used specifically to forecast technologies, processes and skills needed for an effective asset care strategy.

2.3.1 *Knowledge Asset Map*

The literature review did not identify a technology roadmap specifically for maintenance practices in digitized manufacturing. Qin, Liu, and Grosvenor (2016:173) highlight the lack of clarity in both industry and academia regarding the roadmap for achieving Industry 4.0. Phaal et al. (2004:9) emphasize that technology strategy should be integrated with business strategy to ensure alignment and sustainability, a view supported by Ramkirpal (2019). A layered technology roadmap aligns technological advancements with business objectives over time, facilitating technology scanning and influencing acquisition decisions, particularly when equipment reaches the end of its lifecycle (Ramkirpal, 2019). As Reliability 4.0 is the output of an asset care system, multiple interconnected elements must be considered in developing a roadmap to achieve machine and equipment reliability.

2.4 *Systemigrams*

A systemigram is a visual or graphical representation of textual data (Blair, Boardman and Sauser, 2007). It demonstrates the overall design or structure of a system (Blair et al., 2007). As mentioned previously, asset care is considered to be a system, and there are various elements that work in tandem to change asset care to achieve reliability. Therefore, this tool is highly applicable for supporting the analysis of data and understanding the interconnectedness and information flows in asset care. As the problem addressed in this research was highly complex, a systems thinking approach was the most applicable.

3. Proposed Conceptual Method

As per the literature review conducted, reliability is achieved via the interconnectedness of technologies and processes. Reliability is seen to be the output of these systems of elements, which have information flowing between them. Reliability comes from an asset care system that is holistically developed and aims to support the overall technology strategy of the organization.

The model presented in Figure 1 aims to show the relational aspects between technology, asset care, asset care strategy, and maintenance execution tasks.

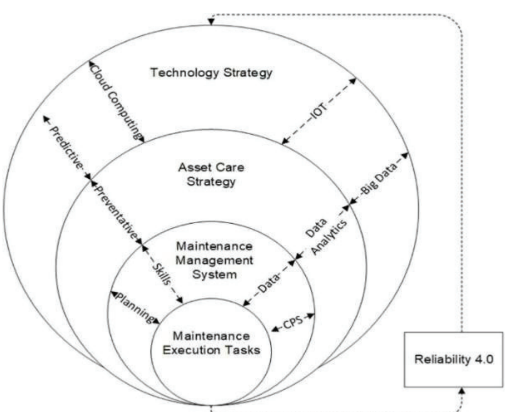

Figure 1: Proposed conceptual model

4. Research Method and Design

The research approach was non-experimental and exploratory. The data was gathered using a structured, targeted questionnaire. A mixed-methods approach was used to analyze the data obtained from the research instrument. Statistical methods and bar charts were applied to understand the salient points of the data. The data was then used to create a systemigram. The panellists selected to participate in this research were all engineers and were required to have a technical tertiary qualification, as well as a certain level of management experience. The structured questionnaire was distributed to 30 with a response rate of 53.3%. As the respondents were considered experts in this subject matter, this rate was seen as acceptable. A Cronbach's alpha of 0.691 was obtained, which is seen as an acceptable measure of internal reliability.

5. Results

The research questionnaire was structured to determine the current state of the organization. The various scenarios and judgements proposed illustrated the impact of digitized manufacturing on the organization's current maintenance systems. The responses were used to create a systemigram of the organization's current state. An ideal state was then proposed based on the literature review. The systemigrams were compared to determine the gaps between the current state and the ideal future state. It is proposed that this gap could be addressed by applying an asset care roadmap that shows the various steps that should be undertaken.

The results analyzed showed that the majority of respondents felt that a strategy for Industry 4.0 existed within the organization. 68.75% of respondents indicated that varying degrees of a strategy existed versus 31.25% that indicated no strategy existed

Although a unanimous response was expected, discrepancies emerged in respondents' awareness of asset care systems, highlighting gaps in communication and stakeholder engagement. These gaps may stem from ineffective dissemination, overly complex frameworks, or misalignment with the organisation's vision. Additionally, the absence of an Industry 4.0 strategy suggests that the asset care roadmap may be outdated. Despite having a roadmap, 56.25% of respondents indicated that environmental scanning and benchmarking were not conducted, implying that the roadmap lacks a holistic, technology-driven approach. Preventative maintenance remains the primary strategy, supported by intelligent data and computerized maintenance management systems. While 75% acknowledged the presence of discrete Industry 4.0 technologies, 81.25% confirmed a strong reliance on cyber-physical systems (CPS) in production processes, indicating a partial but unstructured adoption of Industry 4.0.

Respondents indicated that while machine feedback signals were in place and upgradeable, 50% stated that machine-to-machine (M2M) communication systems were only functionally available. Similarly, 50% viewed data logging systems as largely upgradable, with 43.75% confirming existing functionality. The adoption of Industry 4.0 technologies appears to be driven by technology creep rather than a strategic acquisition process, raising concerns about obsolescence and support capabilities. The organisation is seen as highly reliant on CPS, with PLC technology being the most prevalent. A majority confirmed that data from these systems informed maintenance tasks, and 81.25% indicated that production data influenced maintenance decisions. Furthermore, 87.5% agreed that Industry 4.0 technologies positively impacted productivity, with 62.5% stating that their asset care system focused on machine integration, reinforcing the pivotal role of data in driving reliability.

87.5% of the respondents also indicated that they believed that an intelligent maintenance system (i.e. a system that was based on reliable machine data) would lead to more efficient maintenance execution. Again, data was seen as the key maintenance input that would result in improved integrity within the organization's asset care system. Data gathered from integrated processes (such as production activities) was viewed as valuable for improving the quality of maintenance-related decisions. The 81.25% of respondents confirmed that the organization's asset care system focused on reducing process variability. Equipment acquisition decisions were also made after considering maintenance-related data. These elements are important when creating a system that is required to drive reliability.

The organisation's skills development plan does not align with a long-term asset care strategy. Respondents indicated that project management and data analytical skills were absent and unlikely to improve. While engineering, control, automation, and IT-related skills existed, they were deemed inadequate. When asked about future skills adequacy, respondents expressed low confidence in the ability of teams to support Industry 4.0 technologies. Despite recognising that a digitised manufacturing environment would require enhanced engineering and project management capabilities, the lack of alignment between skills development, asset care strategy, and future technology acquisition raises concerns about the organisation's ability to sustain Reliability 4.0.

The problem statement states that organizations are caught between wanting to do something to change their current systems and not knowing what needs to be done. This paradox extends into the asset care system, as indicated by the research data obtained. It is evident that the organization has attempted to use technology. Still, as they lack an effective technology strategy to guide their asset care system, their effects are not considered fruitful. Systemigrams were applied to view the system holistically and to determine if there were key considerations that should be added to the proposed conceptual model.

There were two systemigrams drawn. The first systemigram incorporates the various elements discussed above and represents the 'current state' of the organization.

The literature review inferred that the ideal state of an organization's asset care system should include the same elements as described above, i.e., Industry 4.0, skills, processes, data, and inherent technology. Figure 2 shows how these elements should evolve from the current state to create an 'ideal system' that sustains a state of Reliability 4.0. Once again, the flows are bi-directional. This implies that the system is dynamic. The asset care strategy is central and influences the asset care system.

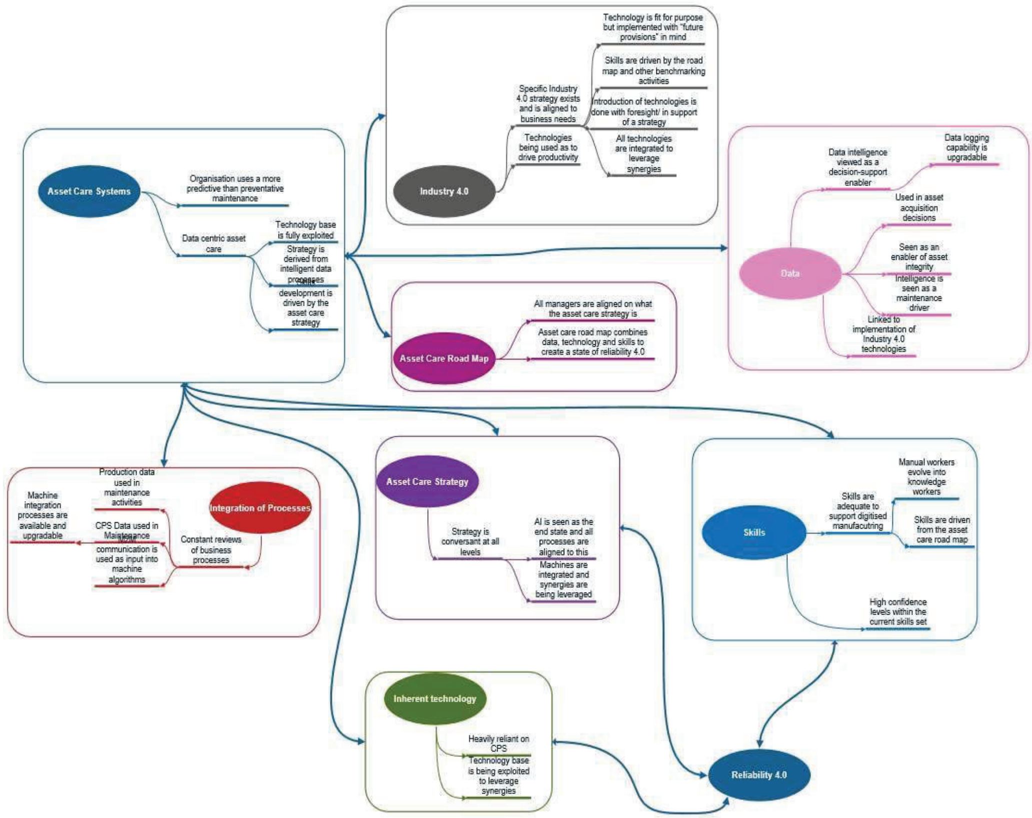

Figure 2. Systemigram of the proposed 'ideal asset care system'.

6. Review of the Conceptual Model

6.1 *Shortcomings of the Initial Model*

While the conceptual model presented in Figure 1 was effective for analyzing the information flows between the various systems within the organization, it lacked the elements identified in the systemigram. These elements were derived from the responses obtained using the research instrument. The model shows the evolution of data and links specific technologies but does not show how processes upstream and downstream are affected.

This model was found to be too internally focused, and it failed to show a link to technology roadmapping, as well as internal and external business processes. The model also considered maintenance-related activities as sub-processes, as opposed to how they can be used to influence the system as a whole. As the aim of this research was to provide a holistic framework to support organizations in achieving Reliability 4.0, a new model was developed for this purpose. Therefore, a new model was proposed, and this will be discussed in the sections that follow.

6.2 *Discussion of the New Proposed Framework*

The new model presented in Figure 4 addresses the shortcomings of its predecessor. Figure 4 shows blue arrows that point to Reliability 4.0. The blocks within the state show how these elements can be used to fit into an asset care system that ensures Reliability 4.0.

The application of this model results in an asset care roadmap that can help organizations develop their asset care strategies to achieve Reliability 4.0

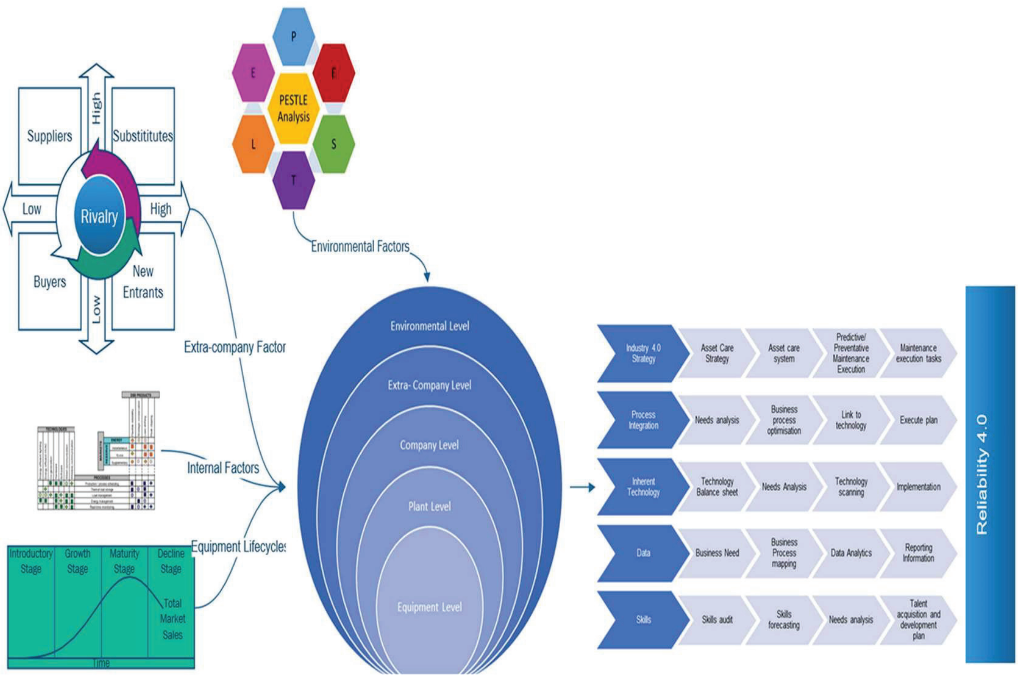

Figure 4: Final conceptual model

7. Conclusion

7.1 *Summary of the Research Objectives*

While there is much anticipation of the implications of the Fourth Industrial Revolution (4IR), very little practical research has been done to analyse the impact of Industry 4.0 technologies on asset care systems. Industry 4.0 is expected to improve asset care reliability (Reliability 4.0). As equipment reliability is the output of a system, the factors that influence this system need to be explored.

This research aimed to address this gap in knowledge by applying technology management tools to develop a framework that organizations can use to support their journey to Reliability 4.0. This research has proven that the predictability element of Reliability 4.0 is derived from the analysis of data that is generated from the outputs of Industry 4.0 asset care systems, which will evolve to become more reliant on equipment that can generate larger amounts of reliable data.

Organizations must critically assess their data sources, intended applications, and integration into asset care strategies. Reliability 4.0 is built on the synergy between production and maintenance activities, evolving these functions into complementary, predictive processes that enhance supply chain efficiency. To achieve this, organizations must fully exploit their baseline technology and align it with an asset care roadmap that considers innovation trends, environmental constraints, and skill requirements. Without such a roadmap, there is a misalignment between technology acquisitions and workforce capabilities, limiting the organization's ability to sustain a digitized maintenance environment.

The absence of a structured technology roadmap also results in fragmented technology investments that do not align with long-term organizational goals, ultimately slowing progress toward Reliability 4.0. An effective roadmap should not only guide asset care strategy development but also integrate business process optimization to enhance data gathering from interconnected processes. By leveraging existing technological infrastructure and aligning technology strategy with skills development, organizations can systematically transition toward a predictive, data-driven asset care system that supports Reliability 4.0.

7.2 *Possible implementation challenges*

Implementing the Reliability 4.0 model presents technological, organisational, financial, and regulatory challenges. Key barriers include system incompatibility, poor data quality, and cybersecurity risks, which hinder seamless integration with asset care strategies. Regulatory complexities, particularly in environmental, health, safety, and data privacy compliance, add to the difficulty. Additionally, upskilling employees and enhancing cybersecurity require significant investment in both time and cost.

7.3 *Recommendations for Further Research*

The research confirmed that while all respondents acknowledged the existence of an asset care strategy, 12.5% were unaware of its details, suggesting potential gaps in communication. Further research could explore the relationship between employees' roles, experience, and their awareness of the strategy to assess the effectiveness of information dissemination. Additionally, the increasing reliance on cloud-based storage introduces cybersecurity risks, as remote access to data and machinery poses potential security threats. Future studies should investigate how asset care systems can integrate cybersecurity measures to safeguard critical data while supporting Industry 4.0 advancements.

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