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Conceptualizing maintenance knowledge and learning in digitalized production

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Abstract. Maintenance knowledge and learning are essential within maintenance organizations, as they drive broader organizational learning and facilitate maintenance digitalization. However, accelerating technological development challenges maintenance organizations in new ways, particularly in learning how to maintain data-driven factories. Maintenance operations require both manual dexterity for repair work and human ingenuity for complex problem-solving. This positions maintenance organizations as learning entities that can also drive learning across the wider organization. In digitalized production, a successful maintenance organization is therefore a learning organization. Despite this, scholars remain uncertain about the levels and organizational interfaces where maintenance knowledge and learning need to occur to facilitate maintenance digitalization. In response, this study aims to conceptualize maintenance knowledge and learning in digitalized production. We focus on how maintenance knowledge should be understood, shared, and utilized, and on why learning within maintenance organizations, between maintenance organizations and other organizational functions, and from maintenance knowledge and learning facilitates maintenance digitalization. Using conceptual modeling, we draw on fundamental theories from knowledge management and organizational learning within the context of maintenance operations in industrial manufacturing. The resulting conceptual model clarifies where knowledge and learning occur and explains how maintenance organizations act as central drivers of learning beyond their own boundaries. The study contributes by providing a shared conceptual understanding of maintenance knowledge and learning in digitalized production for both scholars and industry professionals.

1 Introduction

Maintenance knowledge and learning are essential for all industrial maintenance organizations aiming to keep production up and running. Maintenance refers to the combination of all technical, administrative, and managerial operations performed to preserve and restore assets to a condition in which they can perform their intended functions [1]. Maintenance in industrial manufacturing should therefore be carried out regularly to ensure that production equipment remains in its desired state. However, this is easier said than done, as maintenance organizations are under significant pressure to preserve and restore production equipment as quickly as possible. Often, this causes organizational functions to perceive maintenance operations as a 'necessary evil' [2], thus hindering maintenance organizations from taking time for knowledge and learning. As technological development accelerates and production speeds up, this pressure becomes increasingly problematic, placing new demands on maintenance organizations in digitalized production [3]. In this paper, digitalized production refers to the use of digital technologies in industrial manufacturing to enable connected and data-driven production processes [4, 5].

Maintenance organizations must, to some extent, reorganize themselves to enable effective maintenance knowledge and learning in digitalized production. Unlike production operations, maintenance operations cannot be automated in the same way. For example, breakdowns of production equipment can occur in millions of different ways, where maintenance operations require manual dexterity for repair work and human ingenuity for complex problem-solving. This positions maintenance organizations as learning entities that can also drive learning across the wider organization. A successful maintenance organization in digitalized production is therefore a learning organization. However, becoming a learning organization is challenging and does not happen overnight [6], and scholars remain uncertain about the levels and organizational interfaces where maintenance knowledge and learning need to occur to facilitate maintenance digitalization [7]. In this paper, maintenance digitalization refers to the technical, organizational, and social developments of maintenance organizations driven by digitalized production. Fortunately, knowledge management [8] and organizational learning [9] are well-established research domains that can help explain maintenance knowledge and learning in digitalized production and thereby facilitate maintenance digitalization.

Based on this, we submit that it is unsustainable to continue relying on traditional structures to enable effective maintenance knowledge and learning in digitalized production. Simply put, today's maintenance organizations cannot keep pace with accelerating technological development through their current ways of working. This constitutes both a practical problem and a research gap: without effective maintenance knowledge and learning in digitalized production, data-driven factories will be very difficult to maintain and may ultimately fail. Consequently, there is a clear need for more research on the levels and organizational interfaces where maintenance knowledge and learning need to occur to facilitate maintenance digitalization – namely, how maintenance knowledge should be understood, shared, and utilized in digitalized production, and why learning within maintenance organizations, between maintenance organizations and other organizational functions, and from maintenance knowledge and learning facilitates maintenance digitalization. For this reason, we aim to conceptualize maintenance knowledge and learning in digitalized production by drawing on fundamental theories from knowledge management and organizational learning, situated within the context of maintenance operations in industrial manufacturing.

To achieve this, we adopt conceptual modeling as our research design [10]. Conceptual modeling is a theory-driven approach used to develop new theoretical insights by integrating and structuring existing concepts and theories. Accordingly, the study can be described as a theory synthesis [10], in which concepts and theories from the selected research domains are systematically combined to conceptualize maintenance knowledge and learning in digitalized production. The conceptual model is theoretical and builds on reflective practice, clarifying the selected theories and explaining how they are interconnected [11]. The selection and integration of concepts and theories followed an iterative and collaborative work process, guided by prior research and domain expertise. The conceptual development was coordinated by a lead researcher and iteratively reviewed and refined by the other researchers to ensure conceptual clarity, coherence, and consistency with the selected research domains. In conclusion, the resulting conceptual model makes important theoretical and practical contributions by providing a shared conceptual understanding of maintenance knowledge and learning in digitalized production among scholars and industry professionals.

The paper is structured as follows: We begin by presenting maintenance in industrial manufacturing as well as fundamental concepts and theories of knowledge management and organizational learning. More specifically, maintenance knowledge is understood as tacit and explicit knowledge, which is shared and utilized through knowledge transfer and co-creation. Regarding maintenance learning, the analysis focuses on formal and informal learning, causation and effectuation logic, and exploration and exploitation. We then conceptualize maintenance knowledge and learning as both an internal maintenance capability and a cross-functional organizational resource, explaining why it facilitates maintenance digitalization in industrial manufacturing. In the end, our paper clarifies the levels and organizational interfaces at which maintenance knowledge and learning occur to facilitate maintenance digitalization, and explains how maintenance functions as central drivers of learning beyond its own boundaries. With this, we present the theoretical and practical contributions of the conceptual model and propose directions for future research.

2 Theoretical background

2.1 Maintenance in industrial manufacturing

Maintenance is an essential function in industrial manufacturing, typically organized either as a distinct organizational function or distributed across several functions, depending on the type of manufacturing. The primary group responsible for performing maintenance is often referred to as the maintenance organization [12], and includes technicians, supervisors, planners, engineers, managers, and directors. Maintenance aims to achieve specific goals, such as preserving and restoring production equipment [13], while also focusing on the means to achieve these goals – that is, determining who, what, when, where, and why maintenance should be performed. This follows a so-called causation logic [14], where goals are defined in advance, and resources are adjusted to meet these goals. The opposite is effectuation logic [14], where the focus is on the available resources and selecting between possible effects that can be created with these resources. Effectuation logic is suitable when goals are unclear, such as during periods of transformation and change. Increased competition, combined with higher levels of automation, has led many manufacturing companies to focus on and improve their maintenance, which can account for up to 40% of production costs [15].

Traditionally, maintenance knowledge and learning in production have primarily been driven by maintenance apprenticeships and on-the-job training, a process that [16] refers to as socialization. Such training is also known as learning in the workplace [17]. In practice, apprentices (for example, an inexperienced technician) shadow their master (for example, an experienced technician or engineer). As the apprentices learn from their master, they gradually begin to take on their own work orders in the workplace. The autonomy of the apprentice is therefore increased step by step [18]. Over time, maintenance organizations accumulate knowledge about how to best perform maintenance in production, leading to increased uptime and reduced downtime. To this day, this can be seen as a best practice for maintenance knowledge and learning in industrial manufacturing [19]. However, maintenance apprenticeships and on-the-job training are very time-consuming learning strategies, making them resource-intensive and costly to structure. It is not uncommon for apprentices to require approximately one year of supervision before they are ready to handle their own work orders independently.

2.2 Maintenance knowledge

2.2.1 Tacit and explicit knowledge Maintenance organizations possess company-specific knowledge and experience in maintaining production equipment, much of which is tacit knowledge utilized in human ingenuity for complex problem-solving [20]. Tacit knowledge can be described as knowledge that is difficult to articulate and communicate. In contrast, explicit knowledge can be characterized as codified knowledge that can be transmitted through speaking or writing [16]. In other words, tacit knowledge is not easily demonstrated to apprentices in maintenance organizations. For example, in many situations, there are no detailed work instructions for carrying out repair work and problem-solving in maintenance operations.

However, scholars have demonstrated the importance of tacit knowledge and its direct influence on maintenance performance [21]. But tacit knowledge needs to be managed differently from explicit knowledge [22], and relying solely on tacit knowledge is risky for manufacturing companies that lack strategies for managing it. Consequently, the maintenance academy, which relies on interrelated tacit knowledge, is often regarded as challenging to manage [23, 24].

2.2.2 Knowledge transfer and co-creation In maintenance organizations, certain standard practices and work procedures need to be implemented and followed, and personnel typically undergo bulk training. This constitutes knowledge transfer and can be viewed as a one-way communication of knowledge [25, 14]. In knowledge transfer, there is a giver and a receiver of knowledge, which may remind some of classroom training. Nonetheless, those who have worked in a maintenance organization know that most maintenance knowledge is created through collaboration between individuals solving real problems, i.e., during repair work. This is known as knowledge co-creation [26, 14], another format than knowledge transfer. In such training, the giver can also be the receiver of knowledge, and vice versa. Much suggests that maintenance is a variant of knowledge co-creation, which means that maintenance knowledge tend to lean more toward knowledge co-creation than knowledge transfer.

However, the effective management of maintenance knowledge in industrial manufacturing requires a combination of knowledge transfer and co-creation. This, in turn, demands a structured approach to coordinate reification and participation in maintenance operations [27]. In knowledge management, reification makes knowledge explicit in artifacts, routines, or documents and complements participation. Excessive reification can reduce commitment and interaction, while too little documentation risks unanchored and non-scalable knowledge. Therefore, managing maintenance knowledge must go beyond reification to capture individuals' participation in problem-solving [28], which aligns with the principles of learning organizations [16].

2.3 Maintenance learning

2.3.1 Formal and informal learning Most maintenance learning takes place among personnel engaged in maintenance operations. This can be regarded as informal learning, which refers to knowledge gained outside formal education, often through daily activities and social interactions [17]. In effect, informal learning, which occurs during repair work, closely resembles knowledge co-creation in maintenance operations. The opposite of informal learning is formal learning, which is organized and repeatable [17] and thus more closely resembles knowledge transfer. For informal learning to be effective in maintenance organizations, strong relationships between individuals are required, as all individuals, in one way or another, depend on each other's knowledge to preserve and restore production equipment. This represents practice-based innovation, which can be seen as learning while working [29]. However, informal learning becomes somewhat problematic as maintenance organizations transform, since progress in maintenance knowledge and learning cannot be easily measured [23].

2.3.2 Exploration and exploitation Maintenance organizations need to accumulate a variety of learning to solve as many different problems as possible – this learning is called exploration [30, 9]. However, to become efficient, ways of working must be built on reliability — this learning is called exploitation [30, 9]. Efficient maintenance operations require mastering exploitation (doing things right), while effective maintenance operations require exploration (doing the right things). In other words, exploration ensures the learning of new things, while exploitation ensures that these things are mastered. Maintenance tools and technologies can be acquired, but learning how to use them effectively rarely follows. Consequently, maintenance organizations must balance exploration and exploitation as they transform and change. Exploiting existing knowledge enables the exploration of new learning, which requires managing both 'old' and 'new' knowledge.

However, it is essential to underline that maintenance learning – whether gained through exploration or exploitation – cannot be automatically shared between individuals, teams, and other organizational functions. Knowledge must first be translated before it can be integrated into another memory [30], which challenges learning within and between maintenance organizations and other organizational functions. Given the variability in everyone's memory (for example, between apprentice and master), overly standardized learning activities are unlikely to be efficient or effective. Instead, maintenance learning should be adapted to the collective experience of those involved in specific maintenance operations.

3 Conceptualization

3.1 Learning within maintenance organizations

Maintenance learning must be organized within maintenance operations and the maintenance organization itself and should therefore be regarded as a form of informal learning in industrial manufacturing. This is particularly important in digitalized production, where technological development accelerates, production equipment is continuously updated, and both 'old' and 'new' knowledge risks become obsolete or lag behind. By leveraging learning within maintenance organizations, changes brought by digital transformation can be used as learning opportunities (for example, how digital work orders are reported and analyzed in real time), thereby enabling effective maintenance knowledge and learning in digitalized production.

It is also essential for maintenance organizations undergoing digitalization to continually assess their balance between exploration and exploitation. Sometimes more exploration is needed, and sometimes more exploitation, depending on changing situations and requirements (for example, the digital maturity of new production equipment). This is one reason why scholars have developed assessment tools for maintenance digitalization [31]. By assessing their current state and future needs, maintenance organizations can function as central drivers of learning beyond their own boundaries in digitalized production.

Furthermore, exploration should occur within maintenance operations and be tailored to individuals' knowledge levels, rather than being limited to specific individuals, teams, or organizational functions. For example, when new sensors or software are introduced, it can be better to group individuals by knowledge level, with less experienced individuals exploiting together and more experienced individuals exploring together. Such an approach enables effective maintenance knowledge and learning through knowledge co-creation and effectuation logic, allowing individuals to share experiences and build on each other's understanding of how digitalized production impacts their maintenance operations.

In conclusion, maintenance organizations in digitalized production should first consolidate maintenance knowledge through exploitation – particularly by addressing chronic failures, which account for most production downtime [32] – before gradually building their capacity for exploration. This sequential learning approach, reflecting ambidexterity in maintenance learning, represents the primary pathway for maintenance digitalization, leveraging the adoption of new maintenance tools and technologies (such as predictive maintenance) without undermining foundational practices in maintenance operations (such as mechanical competencies). In a similar way, reification and participation in maintenance operations support this approach, ultimately enabling effective maintenance knowledge and learning in digitalized production.

3.2 Learning between maintenance organizations

[29] emphasizes that risk-taking is essential for fostering new ways of working, which is particularly important when maintenance organizations aim to digitalize. However, risk-taking in industrial manufacturing can lead to serious mistakes or accidents if not properly managed (for example, deviating from standardized work procedures), as new ways of working may result in unexpected effects. Therefore, learning between maintenance organizations during digitalization should not take place in ongoing maintenance operations without first conducting risk analyses. This can be seen as a reason why many manufacturing companies build pilot stations to first test and later share and utilize their maintenance learnings.

Likewise, we believe that maintenance organizations should first follow causation logic to consolidate foundational practices in their maintenance operations, and then apply effectuation logic to explore new ways of working, i.e., new maintenance tools and technologies. This includes co-creating maintenance knowledge with other maintenance organizations (for example, maintenance schedules for common components). Bringing in external ideas is often valuable for gaining new perspectives and avoiding reliance solely on internal experience, which could result in missing lessons from other successful maintenance organizations or technological trends. While not a one-size-fits-all solution, this approach provides guidance on when to share capabilities with other maintenance organizations (such as failure data), thereby accelerating development cycles and facilitating maintenance digitalization.

That said, learning between maintenance organizations is challenging but essential and should be treated as an important element of the digital transformation. Foundational practices in maintenance operations should be centralized to ensure that new ways of working always comply with risk and safety standards. This is particularly important when learning occurs between maintenance organizations that operate in very different contexts, for example between battery production and automotive. When risks are minimal and synergies are clear, learning should first be decentralized within, and then between, maintenance organizations to balance exploration and exploitation in digitalized production on a daily basis.

3.3 Learning from maintenance knowledge and learning

Drawing on maintenance knowledge and learning is essential for the digital transformation of the manufacturing industry as a whole. Maintenance digitalization is a central part of digitalized production, as new production equipment also requires maintenance to avoid breakdowns. This highlights key areas for improvement in digitalization (such as identifying and preserving critical data streams). As demands increase, learning from maintenance organizations becomes increasingly important. However, this has historically been uncommon in industrial manufacturing [33], although it is now receiving increasing attention [34]. We therefore expect future manufacturing companies to increasingly draw on maintenance knowledge and learning as a central element of their digital transformation strategies (for example, prioritizing the digitalization of A-critical over C-critical equipment).

With this in mind, maintenance knowledge and learning in digitalized production cannot be outsourced but constitute a core responsibility of maintenance management in the digital transformation. Such learning is enabled or constrained by prior managerial decisions [6], requiring maintenance management to actively balance exploration and exploitation throughout maintenance digitalization. This, in turn, demands a solid understanding of production equipment health (for example, how process–product relationships influence maintenance operations). Ultimately, maintenance digitalization is not only about implementing digital tools and technologies, but about using them as learning opportunities to address real problems, supported by strategy development processes for maintenance digitalization [35].

We therefore argue that manufacturing companies need to recognize the significant potential of learning from maintenance knowledge and learning, use it as a source of organizational competitiveness, and thereby drive learning across the wider organization. For example, maintenance personnel should be incorporated into the early design process of new production equipment to ensure that it is ready for maintenance digitalization. This is a problematic situation, as production equipment is often designed years before insights from maintenance can be applied. Still, if maintenance knowledge and learning are not incorporated into procurement, maintenance digitalization will be somewhat constrained, and digitalized production may ultimately fail.

4 Discussion

4.1 Theoretical contribution

Building on the theoretical background and our conceptualization, we develop a conceptual model of maintenance knowledge and learning in digitalized production. It draws on fundamental theories in knowledge management and organizational learning, as well as on reflective practice in maintenance operations in industrial manufacturing, to clarify and explain how these are interconnected. The model clarifies the levels and organizational interfaces where maintenance knowledge and learning need to occur to facilitate maintenance digitalization. This constitutes a novel theoretical contribution. The conceptual model is visualized in Figure 1 and discussed below.

Maintenance knowledge in digitalized production results from maintenance learning in digitalized production. The majority of this knowledge is tacit and co-created within maintenance organizations, which is represented by a larger box, and most of this learning is informal. In digitalized production, effectuation logic explores learning through new ways of working, tools, and technologies, while causation logic exploits it. Maintenance knowledge and learning must be balanced between exploration and exploitation to facilitate maintenance digitalization. This sequential learning approach reflects ambidexterity in maintenance learning.

4.2 Practical contributions

The conceptual model makes three practical contributions for industry professionals. First, it emphasizes the need for maintenance supervisors to create sufficient space within maintenance operations and to balance exploration and exploitation to enable effective maintenance knowledge and learning in digitalized production (For example, maintenance schedules can include

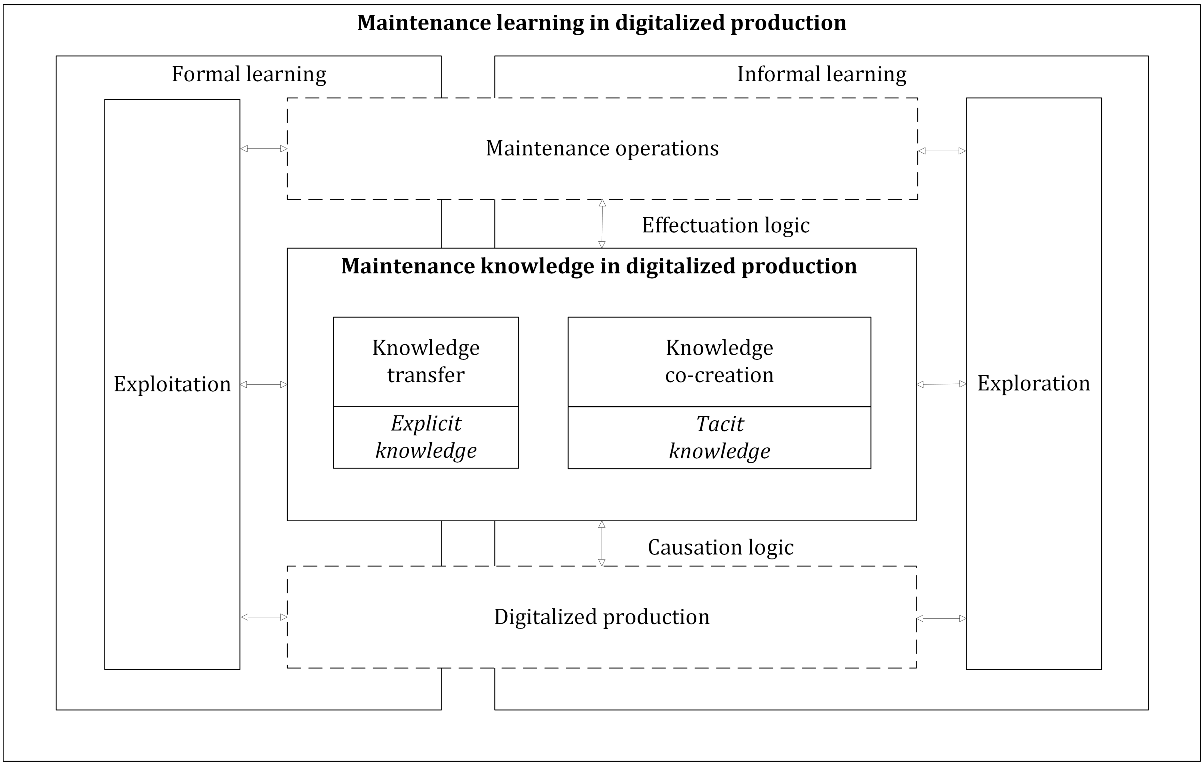

Figure 1: Conceptual model of maintenance knowledge and learning in digitalized production.

different learning activities, such as shadowing). Second, it highlights that maintenance knowledge and learning represent both an internal capability and a cross-functional organizational resource for digital transformation strategies, requiring collaboration both internally (for example, maintenance engineers joining design reviews with production and process engineers) and externally (for example, maintenance organizations located in the same city or region can share capabilities). Third, it reminds maintenance directors that maintenance knowledge and learning in digitalized production cannot be outsourced; rather, it constitutes one of their primary responsibilities in the digital transformation (for example, prioritizing which production equipment requires higher levels of monitoring). Effective maintenance knowledge and learning in digitalized production serve as a strategy for organizational competitiveness, drive broader organizational learning, and facilitate maintenance digitalization.

4.3 Future research
We propose three avenues for future research to enhance maintenance knowledge and learning in digitalized production. First, the conceptual model requires validation to assess its theoretical contribution. As a novel model, it invites interdisciplinary research to explore these concepts and theories and their interconnections. Second, the model should be tested in real manufacturing contexts, considering the type of manufacturing system (e.g., discrete, batch, continuous, or job shop production), to better understand its practical contributions. Third, its internal complexity and dynamics need to be mapped to refine it further and provide more guidance for both academia and industry. This includes, but is not limited to, analyzing tensions (such as centralization vs. decentralization and formalization vs. improvisation), interfaces (between individuals, teams, organizational functions, and new digital technologies), and other industrial

dilemmas (maintenance operations are often perceived as a 'necessary evil' by organizational functions). We conclude that these three research avenues broaden knowledge management and organizational learning in maintenance engineering, enable effective maintenance knowledge and learning in digitalized production, and facilitate maintenance digitalization in industrial manufacturing.

5 Conclusions

To enable effective maintenance knowledge and learning in digitalized production and thereby facilitate maintenance digitalization, maintenance organizations must become learning organizations. Based on fundamental theories in knowledge management and organizational learning, situated within the context of maintenance operations in industrial manufacturing, we conceptualize maintenance knowledge and learning in digitalized production. The conceptual model clarifies the levels and organizational interfaces at which knowledge and learning occur in maintenance organizations in digitalized production, and how these organizations function as central drivers of learning beyond their own boundaries, thereby facilitating maintenance digitalization. The model is novel in its kind, relating knowledge management and organizational learning to maintenance engineering, thereby addressing a practical problem and closing a research gap. We argue that this conceptual model makes important theoretical and practical contributions by providing scholars and industry professionals with a shared understanding of maintenance knowledge and learning in digitalized production.

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Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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