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Worker attributes and training needs for maintenance technicians: insights from lithium-ion battery production

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ABSTRACT

This study examines maintenance technicians in Sweden's emerging lithium-ion battery industry, focusing on desired worker attributes and training needs. Using a single case study at a gigafactory, we collected qualitative data from 21 interviews and two site visits and interpreted them using narrative and thematic analysis. Drawing on industrial maintenance and strategic human resource management literature, we first develop a conceptual framework of the individual-level capacity of maintenance technicians and their Knowledge, Skills, Abilities, and Other characteristics (KSAOs). We then empirically derive the first LIB-specific KSAO profile for technicians by identifying, describing, and classifying 21 worker attributes, as well as uncovering training-related challenges and opportunities. By synthesizing theory and findings into practical KSAO and training frameworks, we provide a rich understanding of worker attributes and training in a novel, dynamic, and highly technical industrial environment, along with a new research foundation linking industrial maintenance and strategic human resource management.

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1. Introduction

Maintenance is an indispensable support process in manufacturing, serving a fundamental role in meeting production targets and preserving cost control. Without effective maintenance, manufacturers face significant challenges in achieving desired levels of operational efficiency. Nevertheless, scholars widely recognize that, against the backdrop of conventional work methods and historical performance benchmarks, labor productivity in maintenance operations must drastically improve to meet the progressively tougher targets of modern manufacturing (Akkermans et al., 2024).

Maintenance technicians constitute the largest labor component within the maintenance function in manufacturing organizations and thus a primary determinant of overall labor productivity. They are the frontline, hands-on workforce directly responsible for essential shop floor maintenance tasks such as inspections, repairs, and replacements. The technicians typically represent half to two-thirds of the maintenance workforce (Plant Engineering, 2021; SMRP, 2017), performing much of the active wrench time and accounting for a substantial share of direct labor costs. While contemporary scholarly literature primarily expects productivity improvements in maintenance operations to materialize from technological advancements (Roda & Macchi, 2021; Silvestri et al., 2020), we submit that human resources will continue to be vital for various maintenance tasks and remain a crucial factor in productivity improvement.

Despite increasing automation capabilities of emerging technologies for both routine and non-routine tasks (Acemoglu, 2025) and their potential to fundamentally alter the way human capital is managed in industrial plants (Ammirato et al., 2023), maintenance technicians' work will (for the foreseeable future) still depend on indispensable human attributes. From a strategic human resource management (SHRM) perspective, this implies that emerging technologies do not eliminate the need for humans but rather change how critical worker attributes should be developed, deployed, and renewed within maintenance organizations (Kim et al., 2025). Cognitively, maintenance technicians troubleshoot complex breakdowns in which even the most sophisticated

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technologies predict probabilistically (Van Oudenhoven et al., 2023) and make contextual risk, safety, and repair judgments that combine sensory information with experience-based heuristics under time pressure (Zhang et al., 2024). Physically, they exploit manual dexterity to perform reliability- and safety-critical maintenance interventions in sensitive and variable environments (Gamer et al., 2020). Thus, maintenance technicians' work heavily relies on job-specific attributes and experiential learning, which SHRM research has long identified as mechanisms for linking human capital resources to performance (Jiang et al., 2012).

Thus, understanding the nature of maintenance technicians' work is central to prescribing what resources and support workers need to perform at work (Brannick et al., 2012). From an SHRM standpoint, this challenge reflects a broader strategic concern with the access to and development of critical human capital resources needed to sustain performance (Boon et al., 2018; Harney & Collings, 2021). Accordingly, the research gap this article seeks to address is how manufacturers can and should ensure access to qualified maintenance technicians and improve their recruitment and training processes – a need repeatedly emphasized in the maintenance literature (Aktef et al., 2025; AnTosz, 2018; Di Pasquale et al., 2024; Razak et al., 2011; Tretten et al., 2025) but largely unexplored specifically at the intersection of industrial maintenance management and SHRM.

To address this gap, research is needed to develop new frameworks for understanding worker attributes and training needs for maintenance technicians. Therefore, this study examines the role of maintenance technicians in the emerging European lithium-ion battery (LIB) industry, specifically in Sweden. Through a case study at a battery gigafactory, we aim to uncover the desired worker attributes and training needs for maintenance technicians in this context. This industry provides an interesting and important context for scientific inquiry (Johns, 2006), reflecting a sensitive industrialization process in greenfield factories, involving design, construction, and ramp-up of complex production and tough operational targets to scale maintenance best practices amid global talent competition, mobility, and resource constraints (Bokrantz et al., 2024). The context offers the opportunity to analyze how a large number of maintenance technicians are recruited, trained, and integrated into a cross-cultural, highly specialized, technical environment that requires intelligent and up-to-date workers capable of collaborating with machines and emerging technologies (Dahmen et al., 2024). Furthermore, the research gap of access, recruitment, and training of maintenance technicians (Tretten et al., 2025) is aggravated in the LIB context by labor shortages (Ragonnaud, 2025), significant downtime costs and scaling challenges (Heiler et al., 2024), and a lack of clarity in competence profiles for maintenance workers (Albatts, 2021). Thus, understanding worker attributes and training needs in this context enables maintenance researchers to better and more broadly inform manufacturing firms about effective workforce development amid increasing demands for upskilling, adaptation, and organizational change.

Through our conceptual and empirical analysis, we make four key contributions to the literature at the intersection of industrial maintenance and SHRM. First, we review and engage with prior literature to outline a theoretically grounded framework that conceptualizes the individual-level capacity of maintenance technicians and anchor it to the context of maintenance technicians in battery production (Section 2). Second, we empirically uncover the desired worker attributes of maintenance technicians; classify their essential knowledge, skills, abilities, and other characteristics (KSAOs); and identify challenges and opportunities associated with training (Section 4). Third, we synthesize our findings into practical KSAO and training frameworks to support managerial decision-making (Section 5). By developing the conceptual framework and illuminating it empirically, we combine existing KSAO theory with the LIB context in a novel way to create a rich understanding of worker attributes and training needs for maintenance technicians. Fourth and finally, we outline a set of research directions aimed at stimulating further scholarly work on SHRM in battery production and maintenance operations more broadly (Section 6). Overall, our study provides new and valuable insights into worker attributes and training specific to maintenance technicians, as well as favorable conditions for improving labor productivity in maintenance operations in a wider context.

2. Theoretical background

2.1. Maintenance technicians in manufacturing

Maintenance technicians are essential to manufacturing efficiency. By performing preventive and corrective maintenance tasks, such as troubleshooting, repairs, inspections, lubrication, and calibration,

technicians keep machinery and equipment operating optimally (Kent et al., 2018). The quality of their work increases productivity, ensures environmental compliance, and prevents safety hazards (Bengtsson & Berglund, 2024). Technicians handle diverse machinery and equipment with varying technical features, operating modes, and degradation patterns, and their hands-on tasks remain among the least automated in manufacturing (Tien & Prabhu, 2018). They also collaborate closely with operators, engineers, and other technical teams to detect and diagnose equipment and implement improvements, making their collective capabilities a strategic asset.

The complexity of technicians' work and the need to handle both planned and unplanned work orders require a broad set of worker attributes that map directly onto essential maintenance performance outcomes. For example, skills in inspections, lubrication, and replacements increase equipment reliability, as reflected in, e.g. the mean time between failure (MTBF), and skills in rapid troubleshooting and corrective actions reduce repair lead times, as reflected in, e.g. the mean time to repair (MTTR) (Refaiy & Labib, 2009). As the quality and breadth of technicians' human attributes lead to faster and more accurate maintenance interventions, they act as important determinants of equipment reliability and availability (Duarte & Santiago Scarpin, 2023). Furthermore, the technicians' ability to keep machinery in optimal condition not only reduces downtime but also ensures product quality and preserves operational performance, thus having a major impact on overall equipment effectiveness (OEE) (Ylipää et al., 2017).

However, there is a well-known shortage of maintenance workers with the right qualifications, education, and experience. For example, manufacturers express concerns about inadequate staff qualifications within maintenance, both at the time of hiring and throughout their careers (Duarte & Santiago Scarpin, 2023); many technicians rely heavily on personal experience (Cárcel-Carrasco & Cárcel-Carrasco, 2021); and internal recruitment from production often yield higher levels of relevant maintenance knowledge than external hiring (Politt, 2010). Similarly, Alysouf (2009) found that few maintenance workers have higher education levels and receive little formal education beyond commercial industry courses, instead mostly learning on the job. Despite the need to overcome worker shortages via continuous and up-to-date training aimed at developing new and wider skill sets (Aktef et al., 2025), the variety of non-routine maintenance tasks and the breadth of cognitive and physical attributes required by maintenance technicians make it increasingly challenging to individualize training and education to specific industrial task environments and worker roles (Di Pasquale et al., 2024). Most manufacturers struggle to systematically identify the desired worker attributes of maintenance technicians and derive corresponding training needs (AnTosoz, 2018). This situation is compounded by limited higher education offerings in maintenance (Kans, 2021) and a shortage of research on vocational training (Bai et al., 2024).

Recruiting, training, and retaining maintenance technicians thus involves major challenges, including but not limited to coping with physically demanding tasks, uncertain career progression, job security concerns, and continuous learning needs (Tretten et al., 2025). While educational resources for maintenance emphasize both formal technical skills and knowledge alongside generic skills such as problem solving and team dynamics (Tsang, 2002), maintenance employers have recently focused also on personal qualities as sources of future growth rather than formal qualifications at hiring (Bengtsson & Berglund, 2024) and on preparing workers for more digitalized manufacturing environments (Bokrantz et al., 2020). To this end, research has focused on identifying worker attributes for maintenance in digitalized contexts (Hlihel et al., 2022). Specifically, Benhamza Hlihel et al. (2024) developed a Maintenance 4.0 competency model featuring 19 competencies for technicians, covering technical, personal, social, and methodological dimensions and including (but not limited to) process understanding, digital skills, continuous learning, communication, and problem solving.

Maintenance of battery production, the specific setting of this study, is a high-complexity environment with strict quality, safety, and environmental requirements (Ju et al., 2015) and major reliability challenges (Attia et al., 2025). Complications with charged cells can lead to serious safety incidents such as fires, explosions, and the release of toxic gases and liquids (Abraham, 2023), and technicians therefore often work in pairs or small teams. Battery production also demands a highly controlled environment free from contamination, moisture, and solvent residues (Örüm Aydın et al., 2023), and the fast-paced production processes require skilled technicians who can quickly address and resolve issues (Albatts, 2023; Bokrantz et al., 2024).

2.2. Conceptualizing the individual-level capacity of maintenance technicians

To study maintenance technicians with precision, clarity in key concepts needs to be established. The existing maintenance literature lacks this regard and tends to use a variety of terminology for the same, similar, and/or overlapping concepts (e.g. referring to competence, knowledge, and skills interchangeably). This restricts cumulative knowledge creation and consistent interpretations across samples and data. To establish clarity, we draw on recognized concepts from the SHRM literature. Specifically, we introduce the concept of (1) KSAOs, outline how (2) the two dimensions of *specificity* (context-generic vs. context-specific) and *content* (cognitive vs. non-cognitive) help distinguish different KSAOs, and describe (3) the *mode of generation* for producing KSAOs (acquire vs. develop).

The performance potential of individual maintenance technicians is determined, at large, by their capacity, i.e. the maximum performance output that can be expected of an individual in perfect conditions (Marshall et al., 2024). This capacity reflects how much or how well maintenance technicians can perform in their work, and it is determined by individuals' KSAOs (Jiang et al., 2013). The KSAOs are worker attributes (Brannick et al., 2012), wherein a maintenance context *knowledge* refers to declarative or procedural information necessary for performing maintenance tasks (e.g. knowledge of mechanical equipment); *skills* are learned and observable proficiency to perform specific maintenance tasks (e.g. executing machinery repairs); *abilities* are enduring traits that apply to a range of related maintenance tasks (e.g. problem-solving); and *other characteristics*, including personality traits and dispositional attributes that apply to a broad range of maintenance tasks (e.g. values and interests) (Hunter et al., 2012).

SHRM scholarship uses two dimensions to distinguish between KSAOs: specificity and content. The first distinction – *specificity* – separates context-generic and context-specific KSAOs (Boon et al., 2018). Generic KSAOs are tied to broad domains and transferable across tasks, while specific KSAOs are relevant only to narrow domains. For example, maintenance knowledge can be generic (e.g. fundamental maintenance principles) or specific (e.g. how to use particular maintenance tools). Furthermore, generic KSAOs are generally stable; fundamental maintenance knowledge acquired through formal education can be used practically indefinitely, and general cognitive ability remains consistent throughout adulthood and is marginally affected by education or experience. In contrast, specific KSAOs are generally malleable, such as accumulating specific maintenance knowledge needed for a new job or learning how to repair newly introduced machinery (Maurer et al., 2003; Ployhart & Moliterno, 2011).

The second distinction – *content* – differentiates between cognitive and non-cognitive KSAOs (Ployhart & Moliterno, 2011). Cognitive KSAOs represent what a person ‘can do’ and consist primarily of the individual's knowledge, skills, and general mental ability (e.g. intelligence). Non-cognitive KSAOs reflect what an individual ‘will do’ and are composed of personal characteristics and preferences for the type of situations people enter (e.g. occupations and roles) and the persistence with which they pursue those situations. For example, skills influence the efficiency with which maintenance tasks are completed (cognitive, ‘can do’), whereas interests (non-cognitive, ‘will do’) influence a person's preference for certain types of work (e.g. choosing to become a maintenance technician) (Ployhart & Moliterno, 2011).

Next, the *mode of generation* describes when and how KSAOs are formed, with the two main mechanisms being acquisition and development. While different KSAOs are more or less improvable over time (Maurer et al., 2003), *acquisition* is suitable for securing stable, generic KSAOs via hiring and formal education (Ployhart et al., 2011), whereas malleable, specific KSAOs are generated through *development*, such as explicit training and targeted education (Boon et al., 2018). Critically, KSAO generation is cumulative in how generic KSAOs facilitate the creation of specific KSAOs (Ployhart et al., 2011). For example, stable and generic KSAOs, such as cognitive ability, influence the development of malleable and specific KSAOs by enabling faster learning and effective transfer of broad knowledge into increasingly specific knowledge (Ployhart et al., 2011). Thus, general maintenance skills (e.g. inspecting and replacing bearings) facilitate the development of specific skills (e.g. repairing a spherical roller bearing in a conveyor system). KSAOs generation is also dynamic, because it takes time to gradually build and accumulate both generic and specific KSAOs, implying the need to uphold a continuous acquisition and development process that involves both external inputs (e.g. hiring, mobility) and internal growth (e.g. training investments) (Hunter et al., 2012; Maurer et al., 2003).

Time is especially important for KSAO development because most specific KSAOs in professional, labor-intensive settings, such as maintenance, must typically be gained through time-consuming on-the-job training and experience. Importantly, individuals who spend more time in developmental experiences are more likely to identify and excel in the most important KSAOs for the job (Maurer et al., 2003). *On-the-job training* occurs while performing the job in an environment where the training is generalized and combined with colleagues. This integration with the natural work context increases the speed and depth of learning (Ployhart et al., 2011). *On-the-job experience* is especially important for developing specific tacit knowledge. With greater experience, less attention and effort are needed for tasks, allowing individuals to focus on more novel aspects of their jobs and enhance knowledge sharing. Experience is particularly important in team settings (Fagan & Ployhart, 2015) because employees contribute to team outcomes by using their KSAOs and associated experience in relevant situations (Jiang et al., 2013). Thus, a larger group of experienced individuals allows technicians to switch tasks and responsibilities, create better cohesion, and effectively share and transfer knowledge.

Figure 1 consolidates the presented conceptual features into an integrated framework where the vertical axis differentiates specificity (generic and stable KSAOs in broad domains vs. specific and malleable KSAOs in narrow domains), the horizontal axis distinguishes content (cognitive, ‘can do’ KSAOs vs. non-

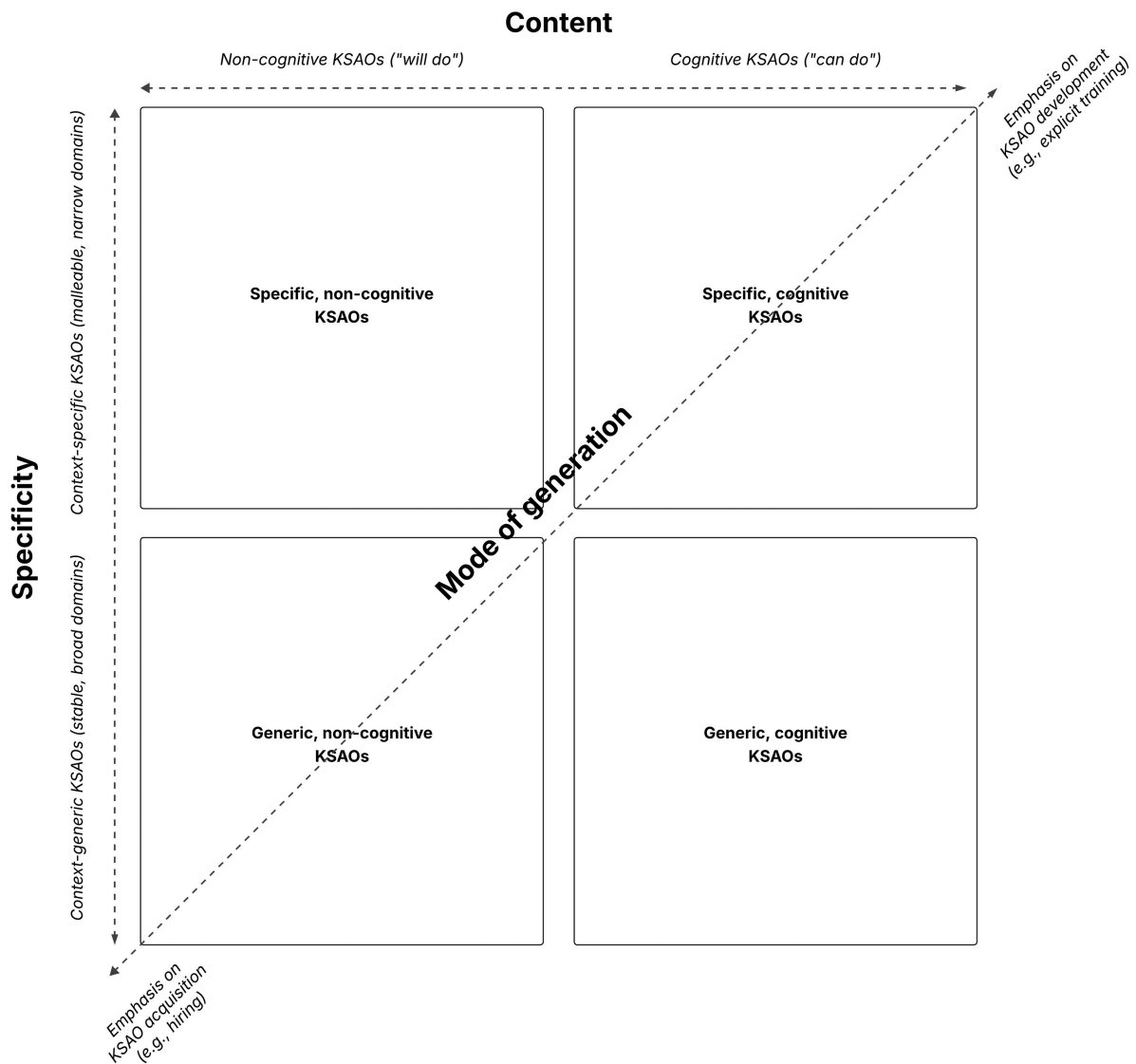


Figure 1. Conceptual framework of the specificity (vertical), content (horizontal), and mode of generation (diagonal) for individual-level KSAOs.

cognitive, ‘will do’ KSAOs), and the diagonal axis specifies the mode of generation (acquisition vs. development and how generic KSAOs facilitate specific KSAOs). The framework serves as our theoretically grounded conceptualization of the individual-level capacity of maintenance technicians as well as the framing of our study's empirical scope, i.e. to uncover the core, desired KSAOs for maintenance technicians in battery production and provide an understanding of how they can be effectively generated through corporate training.

3. Research design and methods

To gain a deep understanding of maintenance technicians in the novel context of battery production, we adopted a single case study design, i.e. a study in which a single case (e.g. a firm, plant) in its real-life context is selected, and data obtained from this case are analyzed in a qualitative manner (Dul & Hak, 2008). Consistent with the well-established case research tradition in operations management, this design is especially justified in situations where the phenomenon is not well understood (viz., maintenance operations in the emerging European battery industry), when rich understanding can be gained through observing actual practice (viz., lived experiences of maintenance technicians in operational gigafactories), and when the objective is to uncover important areas of new research and theory development (viz. training maintenance workers in rapidly scaling greenfield operations) (Voss, 2010).

3.1. Case selection and empirical setting

A necessary and sufficient criterion for identifying a representative case is the ability to study the actual practice of maintenance technicians in operational LIB production. Therefore, we selected an operational gigafactory for battery cell production in Sweden. At the time (Spring, 2024), the firm had completed the construction of its first 16GWh phase; built and commissioned the full operating sequence from electrode production, cell production, and formation and aging; and hired, onboarded, and put to work approximately 300 maintenance technicians during a 4-year period. Thus, the case offered a powerful means for deriving new insights from a single rich case by capturing a novel context where a large number of maintenance workers were hired and trained in a multi-cultural and rapidly growing organization. This occurred in an emerging industry with complex production processes and machinery during a decisive period of new industrialization amid resource constraints (Bokrantz et al., 2024), where the specialized environment of battery gigafactories depends on adequate workforce qualifications and effective corporate training (Dahmen et al., 2024). The empirical phase lasted 5 months, from January to May 2024.

3.2. Data collection

We used two main methods to collect data from people who were best informed about the topic being researched (Voss, 2010): interviews and site visits. The interviews were conducted in two phases. In the first phase, unstructured interviews established a general understanding of the setting and formalized specific directions for the study. Using these insights as input, the second phase focused on illuminating the topic in-depth and consisted of semi-structured interviews with defined protocols. The informants (i.e. individuals providing primary data through interviews) were asked about the KSAOs needed to succeed in battery cell production today, the future KSAOs needed to be in line with increasing digitalization, and their thoughts and experiences with the firm's training. We conducted 21 interviews with maintenance technicians, supervisors, planners, engineers, and managers in different production stages, along with training specialists involved in competence development at the firm (see details in Table 1). All the informants verbally provided informed consent for their participation in the study. This sample size aligns with recent guidelines for reaching saturation in themes and meaning (Wutich et al., 2024). The case firm supported interviewee recruitment by first proposing the most knowledgeable individuals, then we used the interviewees' recommendations to identify others who could complement, expand, or challenge the issues addressed. The interviews lasted between 30 and 60 minutes and were audio recorded and transcribed, except in a few instances where data were recorded as notes upon the informants' requests. The interviews were complemented with two site visits at the beginning (to establish a general

Table 1. Description of informants.

Role	n	%	Role description at the case firm
Technicians	8	38%	Technicians perform inspections, diagnose issues, and carry out repairs to keep equipment running. They handle preventive tasks such as cleaning and lubrication, and contribute to coordinating daily work.
Supervisors	1	5%	Supervisors allocate tasks, manage schedules, and enforce safety. They act as the link between technicians and management to ensure efficient maintenance operations.
Planners	1	5%	Planners design maintenance plans, schedule preventive tasks, and align downtime with production needs. They manage resources, track activities, and monitor spare parts to optimize efficiency.
Engineers	4	19%	Engineers analyze performance, develop preventive strategies, and improve processes. They troubleshoot complex issues, guide technicians, and implement advanced diagnostic tools together with other engineering teams.
Managers	4	19%	Managers act strategically by developing maintenance strategies, managing budgets, and aligning activities with production goals. They focus on equipment reliability, safety compliance, and cross-functional coordination.
Specialists	3	14%	Specialists focus on developing and maintaining training materials, designing programs, and coordinating internal and external activities across the entire factory to support operational excellence.

understanding) and at the end of the study (to collect specific information and verify findings). These visits offered opportunities for direct observations via plant tours and interactions with personnel from different parts of the organization, including the maintenance and training departments.

3.3. Data analysis

Two complementary methods were used for data analysis: narrative (Earthy & Cronin, 2008) and thematic (Naeem et al., 2023). Narrative analysis focused on giving voice to the informants by treating them as knowledgeable agents explaining their thoughts, intentions, and actions. Their lived experiences provide insight into facts, information, emotions, and special meaning that they assign to workplace events (Earthy & Cronin, 2008). We used a categorical approach to narrative analysis that focused on capturing and analyzing shared experiences among targeted maintenance workers, specifically the training process at the firm. The analytical process focused on searching for patterns and constructing meaning in the informants' words by interpreting the content (what they are telling) and structure (how they tell it) of their experiences. Our analysis focuses on capturing the informant's lived experiences, not their underlying reasons or causes.

The thematic analysis focused on identifying specific patterns in the data that could be interpreted as relevant KSAOs of maintenance technicians. Our analytical process aligned with the conventional logic of qualitative data analysis, i.e. progressively moving from initial coding and descriptions towards more refined categorization and higher levels of theoretical abstraction (Cañibano et al., 2025). We first selected quotes, statements, or notes expressing desirable worker attributes; analyzed recurring patterns and similarities among them; and highlighted important keywords (Naeem et al., 2023). For example, the quote 'It's important to have basic mechanical, electrical, and chemical knowledge' contained the keywords *mechanical*, *electrical*, and *chemical*. We then defined theoretical codes for each emergent empirical pattern representing a distinct worker attribute and formulated descriptive summaries. For example, quotes and keywords related to mechanics, combined with our situated understanding of LIB production gained from site visits, served to form the KSAO 'Mechanical' (which includes skills in maintaining mechanically moving parts that require regular inspection, repairs, and replacements; see Appendix A). The coding process was iterative, involved constant comparisons between empirical data and theoretical codes, and was continuously revised and refined as our understanding deepened. We focused on identifying the most significant KSAOs that captured the richness of the context, and we continued until a saturation point where no new core worker attributes appeared (Wutich et al., 2024). Reaching saturation by constantly comparing coding to new data was also reinforced by the iterative and sequential recruitment of informants (see Section 3.2). Thereafter, we classified each coded attribute into the corresponding KSAO type by comparison against the working definitions of KSAOs (see Section 2.2). For example, the attribute 'Mechanical' (see Appendix A) was classified as 'Skill', because it reflects the learned and observable proficiency in executing maintenance on mechanically moving parts and components. This analysis approach ensured that the theoretical interpretations were firmly grounded in the empirical data.

Two researchers jointly performed the qualitative coding, and two additional researchers focused on assessing and verifying its credibility. Multiple techniques have also been used to increase the

trustworthiness of the data and findings and ensure analytical consistency (Halldórsson & Aastrup, 2003). Member checking (Creswell & Miller, 2000) involved iterative feedback sessions with relevant stakeholders at the case firm. Emerging analyses were presented, allowing individuals to react to the findings, share their opinions, and highlight strengths and weaknesses of the interpretations. Peer debriefing (Corley & Gioia, 2004) was used to present and discuss the emergent analyses with research colleagues not directly involved in the empirical study and reflect on their critical feedback. These techniques strengthened the match between data and interpretations and acted as methodological audits of our analytical logic and process. Furthermore, multiple sources of evidence complement each other (Yin, 2013), where interviews contributed most and had higher relative importance by providing first-hand accounts of experiences and processes, and site visits provided situated understanding through in situ plant observations and interactions with key stakeholders. By providing descriptions of the empirical context (e.g. characteristics, location, sample, time) (Cañibano et al., 2025) (Sections 1 and 3), along with the empirical findings (Section 4), we facilitate judgment of the applicability of our insights to other manufacturing settings.

4. Findings

4.1. Capacity and KSAOs of maintenance technicians

The empirical findings and theoretical interpretations are presented in two phases. First, the findings from the narrative analysis focus on representing the informant's voices and experiences, including our interpreted meaning of the informants' words along with exemplar empirical quotes (in italics). Second, the thematic findings consist of the identified and classified set of KSAOs representing core worker attributes for maintenance technicians in battery production.

4.1.1. Narrative findings from experiences and events

Several informants highlighted the central importance of experience when joining as new employees. For technicians, prior maintenance experience increased their learning rate and quality of performing maintenance tasks, and a deeper understanding of how maintenance is performed allowed them to execute their tasks faster and better.

“I understand the problems better because of my experience as a technician and therefore able to work on improvements.”

Furthermore, the informants suggested that experienced personnel are key assets for operational efficiency. Their familiarity with the work environment enables them to operate independently from existing work instructions, thus reducing the need for training and the reliance on specific guidelines. Maintenance experience was perceived to be particularly valuable in scenarios of rapid technological and organizational scaling where experienced individuals demonstrate a robust capacity to manage diverse tasks and contribute to value creation directly.

“Need to have some technical background and it is good if you have worked with maintenance or at least in some kind of factory. The reason is that you are able to learn everything faster if you have relevant experience.”

The value of experienced workers also extends beyond their immediate responsibilities and expectations of their role. They are perceived in the organization as critical actors in knowledge transfer, which is especially notable in the continuity of operations between shifts. Informants described how experienced maintenance technicians also play an important role in teaching and mentoring less experienced co-workers, thus ensuring that expertise and best practices are consistently spread throughout the maintenance workforce.

“There are no dedicated systems for communicating between shifts and therefore are experienced personnel important as they are good with this type of communication.”

The interviews revealed a perceived consensus among the maintenance technicians regarding the nature of their work: the core responsibility of their role lies in the maintenance, repair, and operations of

technical machinery, a task that has remained consistent for decades. The informants' understanding was that this fundamental role of maintenance technicians would persist with little variation in the future.

“Technicians will have only minor updates to their work instructions when working more with data; the biggest changes will be for engineers.”

Mechanical, electrical, and chemical knowledge are seen as key elements for all technicians and essential for carrying out tasks. From the informants' point of view, basic and conventional knowledge in the fundamental areas of maintenance operations was perceived to be an important enabler for employees to develop more specific knowledge at a faster pace. Along with the maintenance fundamentals and associated technical proficiency, the informants also expressed the value and importance of analytical ability and communication skills to address the wide spectrum of possible problems during maintenance tasks and effectively transfer knowledge between employees and shifts.

“It’s important to have basic mechanical, electrical, and chemical knowledge, if maintenance technicians have this knowledge they know when to call for specialists which could end up saving someone’s life.”

Despite this perceived consistency in the maintenance technician role, the informants also noted the increasing complexity of both the machinery in question and the tools required for maintenance, and the new requirements when working in clean and dry rooms. Thus, while recognizing the continued value of conventional maintenance knowledge, the informants also expressed the emergent need for adaptability and a willingness to engage with new processes and methodologies, not least owing to the rapid expansion and construction of facilities for battery production. Notably, working at the firm differs significantly from working at other companies because of the unique situation and nature of the emerging European battery industry. These perceptions reflected a broader trend toward increased emphasis on continuous learning and flexibility within the maintenance workforce.

“Clean and dry rooms are different in battery production compared to other industries.”

As new and more digital technologies emerge in the workplace, both in the production process (e.g. digitally connected machinery) and the maintenance process (e.g. data-driven diagnostics), the informants expressed how the understanding and use of digital tools will increase in importance, especially owing to the potential to avoid machine failures using data analytics. However, the informants did not expect or foresee any major changes to the maintenance technician role or associated expansions encompassing extensive data handling or analysis. Rather, they anticipated that their involvement with data and digital tools would be action-oriented, focusing on responding to and interacting with the information provided. The technicians instead projected that other roles within the maintenance organization would evolve to include the handling, analysis, and application of data for decision-making.

“If you should recruit someone today or in ten years the most important thing is still experience and knowledge within mechanics. You basically want a car mechanic from the 80 s.”

4.1.1.1. Key insights from narrative analysis.

- *Invaluable importance of experience:* Maintenance technicians consistently express how experience enhances their performance in various maintenance tasks, improves the quality of their work, sharpens their operational understanding, and enables them to operate more independently. The accumulation of experience enables technicians to become less reliant on detailed instructions and focus on more complex tasks. Experienced technicians also play a key role in knowledge sharing, development of maintenance best practices, and ensuring smooth transitions across shifts, thus strongly contributing to the efficiency of maintenance operations.
- *Perceived stability in the core role and worker attributes:* From the perspective of maintenance technicians, the essential tasks of machinery maintenance, repair, and operation are expected to remain stable for the foreseeable future. As these core responsibilities are perceived as the foundation of their role, they do not foresee significant changes in the desired worker attributes needed to execute their daily tasks.

- *Emerging specificity and emphasis on behavioral attributes:* Technicians are increasingly recognizing the growing importance of behavioral attributes (or interpersonal skills), such as communication, teamwork, and continuous learning. These non-technical attributes are perceived as crucial for knowledge transfer and ensuring smooth operations across shifts. Many technicians link these attributes to the specificity of their work environment and the natural context of daily maintenance operations.
- *Reserved anticipation on digital disruptiveness:* While industrial digitalization is expected to lead to more digital tools being introduced into the workplace, maintenance technicians generally anticipate minimal disruption in their core duties and expect that their interaction with data will be action-oriented. They do not foresee being engaged in extensive data analysis but rather believe that other roles are experiencing more significant changes as they adapt to digitalization.

4.1.2. Thematic findings of KSAOs

We identified a set of 21 worker attributes for maintenance technicians that reside at the level of individuals and classified each attribute into the KSAO typology. As a quantitative summary, the KSAOs consisted of 5 *knowledge* (24%), 10 *skills* (48%), 3 *abilities* (14%), and 3 *other characteristics* (14%) (classified in Table 2), and they represented the core characteristics of well-qualified maintenance technicians in battery production. Table 2 presents the classified KSAOs with labels (in bold) and concise working definitions, with elaborate descriptive summaries appearing in Appendix A.

4.2. Training needs

4.2.1. Narrative findings from experiences and events

The informants' experiences revealed a common view on the importance of training and the shortcomings of the current training structure. Processes for training maintenance technicians at the firm have evolved

Table 2. KSAOs for maintenance technicians in LIB production.

Knowledge (K)	Skills (S)	Abilities (A)	Other characteristics (O)
Maintenance processes: knowing fundamental processes like planning, scheduling, and documentation.	Mechanical: maintaining and repairing complex moving parts in production machinery.	Analytical reasoning: thinking logically to diagnose faults without clear instructions.	Calm mentality: staying calm and focused under pressure in high-stress situations.
Battery machinery: knowing advanced battery equipment and machinery to maintain and troubleshoot complex machines.	Electrical: maintaining electrical components in production machinery.	Interdisciplinary thinking: combining knowledge from different disciplines to solve complex problems.	Personal drive: taking initiative to solve problems and improve independently.
Clean and dry room protocols: knowing cleanroom protocols to avoid contamination in sensitive environments.	Mechatronic: working with integrated mechanical, electrical, and control systems.	Adaptability: adjusting quickly to new tools, systems, and work conditions.	Strong work ethic: committing to high performance under demanding work conditions.
Safety procedures: knowing safety routines to work safely with hazardous machines and materials.	Troubleshooting: quickly identifying and resolving machine issues to reduce downtime.		
Battery products: knowing how product properties interact with machine performance to ensure quality.	Chemical handling: handling hazardous and reactive materials safely and precisely.		
	Digital tools: using digital tools to improve maintenance interventions.		
	Communication: clearly conveying information across roles and teams.		
	Teamwork: effectively collaborating and coordinating maintenance activities.		
	Continuous learning: learning new tools and practices to keep up with evolving technologies.		
	Teaching and training: sharing knowledge and supporting workforce learning and task handovers.		

dynamically, adapting to the organization's rapid expansion and employing various tools, methods, and techniques to equip new maintenance workers with critical qualifications.

“The current training is too basic and general, which makes people slower to become productive.”

The informants explained how the firm developed their training practices over time, transitioning from an early version consisting of a mix of company orientation, practical on-the-job learning, and hands-on practice alongside production operators, to a more comprehensive and structured training program used today. Currently, the process for new maintenance technicians, visualized in Figure 2, consists of an employment kick-off (‘Charge days’) and an Introductory Maintenance Education (IME) module. This is followed by an onboarding process consisting of a week-long introduction to the firm, presenting its key targets, values, safety routines, and specific knowledge needed. The program is finalized in the factory, where new maintenance technicians work under the supervision of more experienced personnel, first focusing on basic production training and then transitioning to specific maintenance training to gain practical experience and training in troubleshooting equipment. Throughout the full process, educational courses are provided through an online learning management system (LMS).

The full training program extends over several months, starting with educational courses in the LMS during the so-called ‘Charge Days’. The initial courses are designed to familiarize new personnel with the firm's most fundamental and practical knowledge. However, the informants expressed how the effectiveness of the courses is somewhat hampered by the volume of information dispensed in the condensed time frame, causing information overload. This overload was perceived to create a need for additional follow-up training, particularly concerning safety protocols, to ensure that all maintenance employees have the fundamental qualifications needed to start working.

“The Charge Days are too intensive, nobody can process that much information in just a couple of days.”

Thereafter, the IME is mandatory for all new maintenance technicians and is intended to build confidence in handling machinery by creating a fundamental base of maintenance knowledge. However, many technicians expressed concerns about the value of the IME for experienced personnel, given its focus on maintenance fundamentals. The IME training is complemented by in-house sessions focused on developing skills and mindsets related to problem-solving and troubleshooting, incorporating hands-on experiences with specific factory equipment to bridge the gap between theoretical knowledge and practical application.

“It is not possible to train a new employee quickly; hands-on experience is required, and that takes significant time to develop.”

Despite these training structures in place, the technicians consistently described how the current training program fails to provide sufficient hands-on experience before entering the factory. This

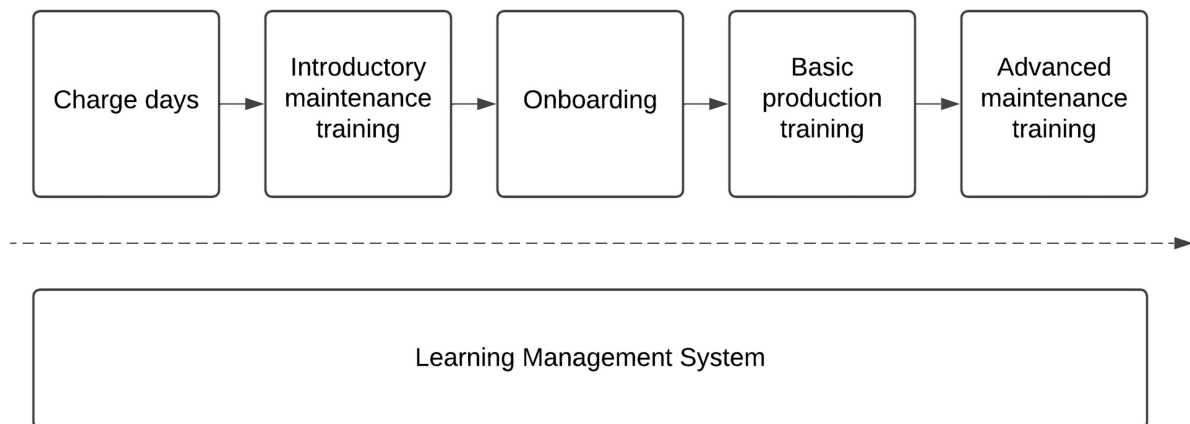


Figure 2. The current training program for maintenance technicians.

mismatch between entry-level qualifications and job expectations is seen as a constraint for the technicians' learning curve, and the informants voiced concern for how this challenge will grow even more as the production site continues to expand.

“People coming from the introductory maintenance education have really limited knowledge.”

The subsequent phases involve new technicians entering the factory and starting to work hands-on under the guidance of experienced trainers, first focusing on basic training in production and then followed by more advanced training in maintenance. These phases critically depend on the experienced employees' ability to teach knowledge and skills effectively.

“Training maintenance technicians is much more complex than training production operators, since a machine can only be operated in one way but can fail in many different ways.”

However, a notable issue expressed by the informants is the absence of a standardized process for this knowledge transfer, where the trainers' personal teaching methods significantly influence training quality and often lead to varying skill levels across teams and shifts. This issue is further aggravated by the lack of detailed information about machine specifications from suppliers, making it challenging for new technicians to apply theoretical knowledge in practical settings. Thus, in combination with the lack of standardization in on-the-job training structures, the absence of machine information, the unpredictable nature of maintenance work, and high workloads, battery manufacturers face large challenges in providing consistent, high-quality training in running production.

“Today a lot is learning by doing and not structured training.”

Reflecting on their own experiences, the informants expressed both shortcomings and merits of the current training program. On the one end, the technicians described several issues with the LMS, including the absence of practical training due to the program's digital structure and the ability to redo knowledge tests with the same questions, which allows for passing the tests through repetitive attempts rather than true understanding. These issues were perceived by the informants as both a quality and a safety risk, and they argued that maintenance technicians need a combination of practical and theoretical training.

“You can take them, LMS, basically a couple of times and at a certain point you will pass. It should not be possible to just try it a couple of times and only learn what's the answer to each question without actually understanding it.”

On the other end, many technicians appreciated the learning approach based on 'shadowing' production operators. This was perceived as resulting in an extensive understanding of machines and the production process, and an effective way of gaining practical experience from running production. Furthermore, the internal hiring of maintenance technicians from the production teams was appreciated, expressed as a means for leveraging the operators' firsthand knowledge of the machinery and operations and establishing good relationships between the maintenance and production departments.

“When I started we worked with operators in the beginning to gain knowledge about the machines. I think this training was really good and gave me the necessary knowledge to solve some problems even more experienced technicians could not handle.”

Several informants also expressed ideas of specific improvements to the training program. A recurring idea was training camps, which were seen as a potential solution to the lack of practical experience when maintenance workers entered the factory. Training camps were seen as a means to provide an intensive period of hands-on training in an environment that closely resembles actual working conditions. For example, inactive production lines could be used as training grounds to enable new employees to acquire practical experience in a controlled environment.

“I believe in camps, this is something currently in preparation for operators. Camps give opportunities to gain hands-on experience, but the production lines currently used have high-performance requirements which does not allow for extra downtime due to training. Therefore, the plan is to use lines currently in construction before they are ready to produce customer products.”

4.2.1.1. Key insights from narrative analysis.

- *Acknowledged training gaps*: significant gaps in technician training programs are acknowledged, particularly concerning practical, hands-on exposure to real-world maintenance tasks. This leaves new technicians underprepared to address the complexities of daily maintenance operations as they enter the shop floor. These gaps highlight the need for more thorough and robust training approaches to ensure that technicians can confidently handle the demands of their roles.
- *Variability in training quality*: a lack of standardized training procedures and over-reliance on individual trainers leads to variability in training quality and thereby noticeable differences in the qualifications of new technicians. Addressing this issue requires a more structured and uniform training approach.
- *Deficiencies in digital learning*: The LMS currently in use falls short in several areas, including the lack of practical training components and reliance on repetitive tests, thereby not sufficiently preparing technicians for the realities of maintenance work. In addition, an over-reliance on digital training is perceived to compromise occupational safety, emphasizing the need for integrating more practical, hands-on elements into the training program.
- *Methods for practical engagement*: To address the gap in hands-on training elements, methods for practical engagement, such as shadowing production operators, could offer new technicians the opportunity to learn by observing and participating in daily operations.
- *Training camps for controlled practice*: training camps that utilize inactive production lines as controlled practice environments could allow maintenance technicians to gain hands-on training without the pressures or risks associated with running production. This could be a way for technicians to gain knowledge and refine their skills before entering live operations on the shop floor.

A summary of our findings is graphically displayed in [Figure 3](#), highlighting the key empirical insights related to the capacity and KSAOs of maintenance technicians and associated training needs.

5. Practical KSAO and training framework

Based on our empirical findings ([Section 4](#) and [Figure 3](#)), we now synthesize our insights into practical KSAO and training frameworks for maintenance technicians.

5.1. KSAO framework

Our empirical findings demonstrate the value of the KSAO concept for substantiating the individual-level capacity of maintenance technicians (Marshall et al., 2024). The insights revealed a perceived stability of the role and worker attributes among maintenance technicians in battery production, even in the face of digital disruptiveness, highlighting generic KSAOs as foundational to human capacity in most professions (Jiang et al., 2013; Ployhart & Moliterno, 2011). In addition, the empirics have shown the importance of on-the-job experience for KSAO development (Ployhart et al., 2011), enabling experienced technicians to better understand maintenance issues, perform tasks more efficiently, and take on team roles for teaching, mentoring, and knowledge transfer. Furthermore, the demand for behavioral attributes and emerging KSAOs specific to battery production illustrates the need to differentiate between KSAOs (Boon et al., 2018; Ployhart & Moliterno, 2011). These findings also corroborate prior research on maintenance technicians highlighting the diverse nature of maintenance worker attributes (Benhamza Hlihel et al., 2024), the foundational importance of maintenance experience (Cárcel-Carrasco & Cárcel-Carrasco, 2021), and the increasing emphasis on behavioral attributes among maintenance employers (Bengtsson & Berglund, 2024).

To further illuminate how the specificity and content help distinguish different KSAOs for maintenance technicians, we map the 21 identified KSAOs ([Table 2](#)) into the typology ([Figure 4](#)). A qualitative (and quantitative summary in brackets) mapping reveals four relevant patterns: (1) an emphasis on cognitive KSAOs (>85% are knowledge, skills, or abilities; right-hand side of [Figure 4](#)), (2) a focus on the general foundation (>75% are generic KSAOs; lower-half of [Figure 4](#)), and (3) knowledge-driven contextualization

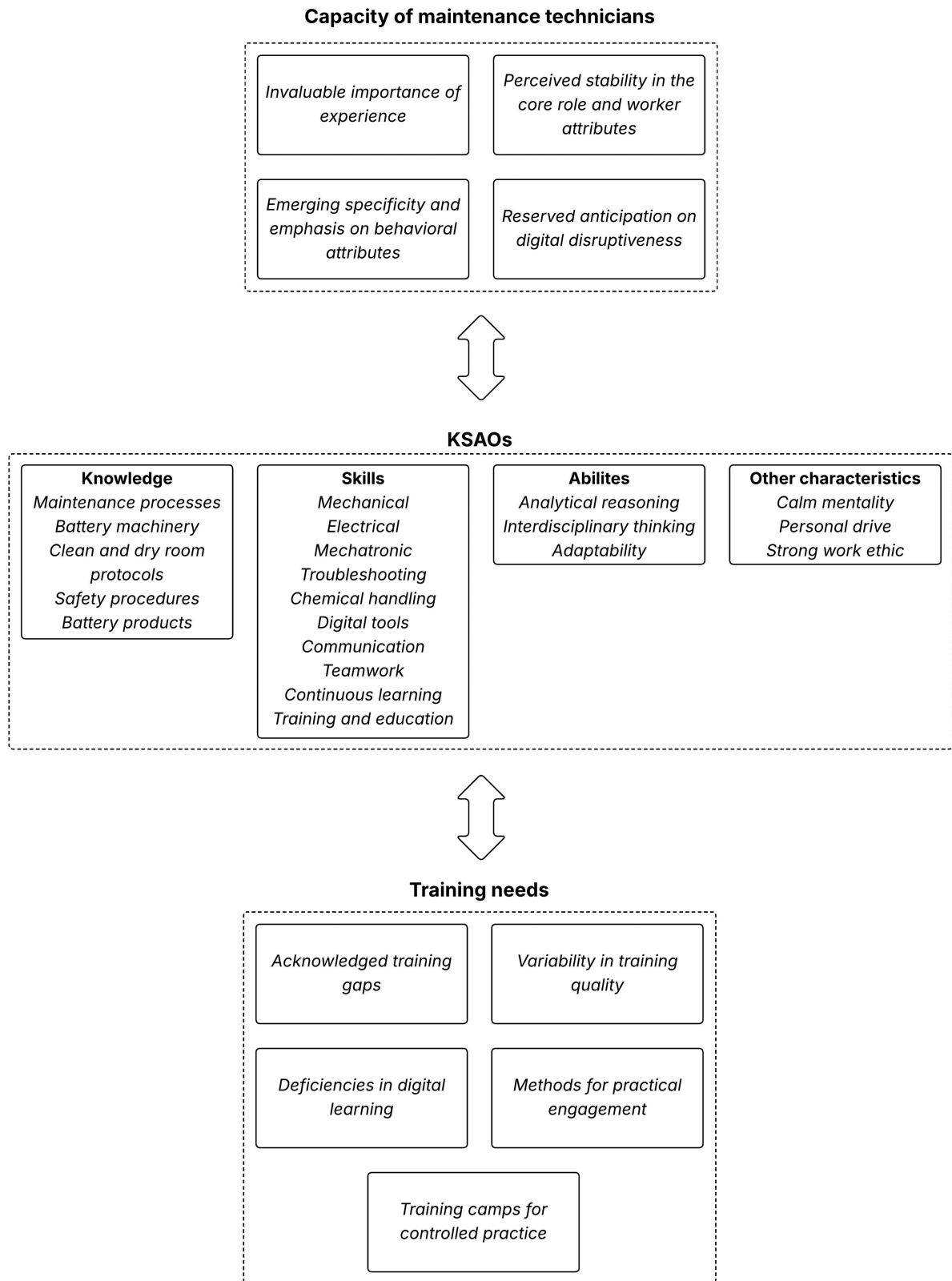


Figure 3. Graphical representation of empirical findings.

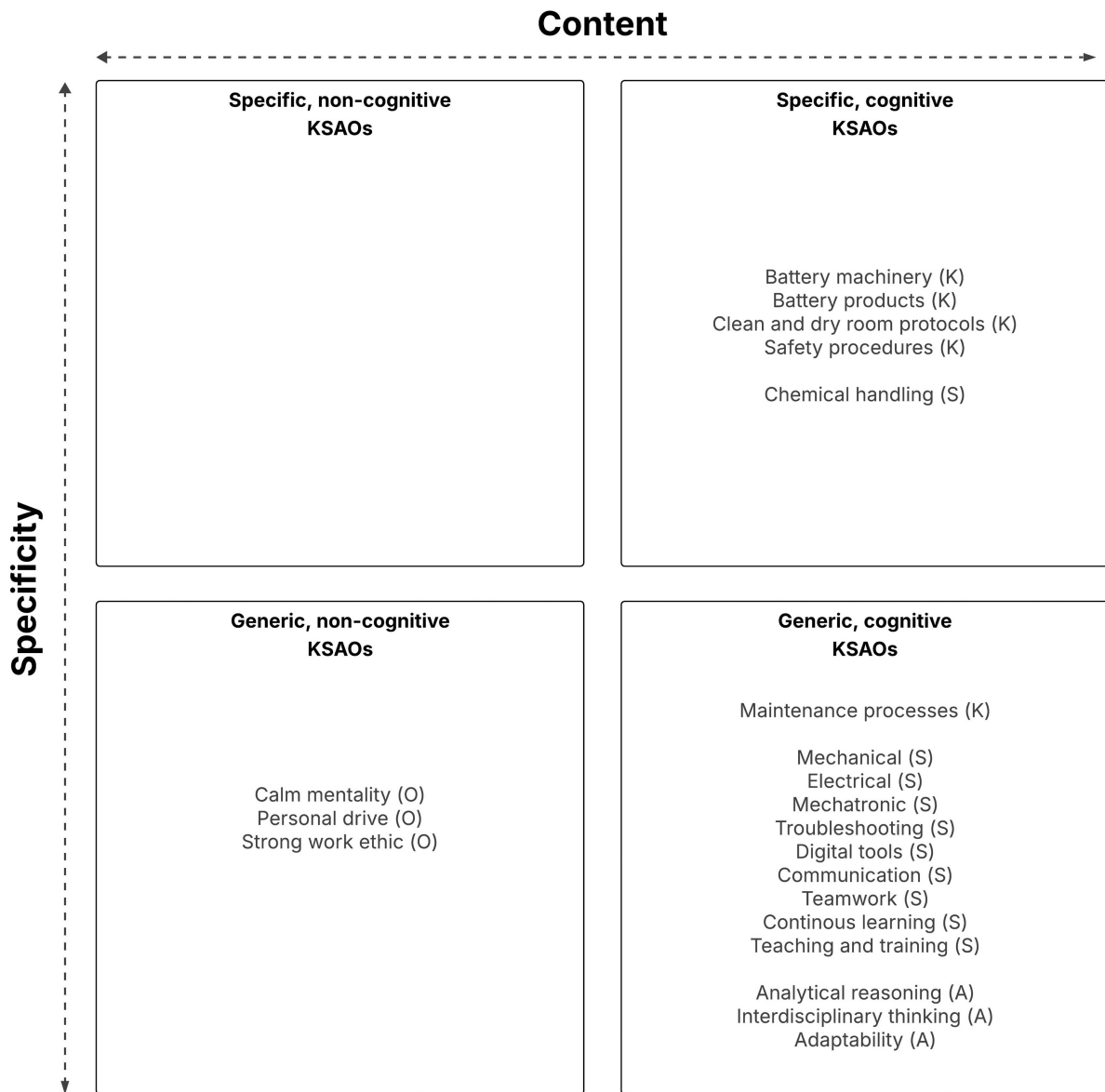


Figure 4. KSAO framework for maintenance technicians in battery production.

(80% of the specific KSAOs are knowledge; upper right of Figure 4), and (4) the absence of specific ‘will do’s’ (zero specific, non-cognitive KSAOs; upper left of Figure 4).

The four patterns have clear implications for *what* worker attributes to prioritize and *how* to generate them. The attributes in Figure 4 form a blueprint for the capacity of maintenance technicians and the proposition that qualified technicians with these KSAOs have higher job performance. Therefore, battery manufacturers should aim to maximize the number of technicians with all desired KSAOs (at justifiable cost). The mix of generic and specific KSAOs (Figure 4) and theory (Ployhart et al., 2011) suggests using both acquisition and development mechanisms (Maurer et al., 2003). Acquisition (e.g. hiring, internal mobility) should focus on non-cognitive ‘will do’ KSAOs (e.g. calm mentality) and generic cognitive ‘can do’ KSAOs (e.g. mechanical skills). Development (e.g. training) should focus on accelerating generic ‘can do’ KSAOs (e.g. troubleshooting) and creating specific KSAOs (e.g. knowledge of battery machinery).

5.2. Training framework

The empirical findings identified training gaps, variability in training quality, and shortcomings in digital learning, emphasizing the need for systematic and tailored programs to generate desired KSAOs. Practical

elements are critical, aligning with the role of on-the-job training and experience for occupations such as maintenance technicians (Ployhart et al., 2011). The mismatch between entry-level qualifications and job expectations, which leaves some unprepared and others finding training redundant, calls for a more flexible, individualized approach. Thus, training programs should combine theoretical and practical elements, be manageable in terms of intensity and duration (e.g. spaced repetition), and avoid a ‘one-size-fits-all’ approach. Broadly, these findings confirm prior maintenance research highlighting the critical role of education and training in maintenance (Tsang, 2002); how recruitment, training, and education are a major challenge for manufacturers (Bengtsson & Berglund, 2024); and how manufacturing firms struggle with ensuring the qualifications of maintenance technicians (Duarte & Santiago Scarpin, 2023). Against the backdrop of our empirical findings and associated theory, we outline a generic training framework for maintenance technicians. The framework links the empirically derived training needs into a theoretical structure for effective KSAO generation. The framework seeks to achieve the outcome of qualified maintenance technicians through the generation of desired KSAOs using three interrelated features (Figure 5): (1) *when*, (2) *whom*, and (3) *how*.

First, the *when* emphasizes sequencing generic and specific training, aligning with the proposition that generic KSAOs facilitate the development of specific KSAOs (Ployhart et al., 2011). Initial training covers broad, fundamental topics to provide a comprehensive understanding of maintenance operations, gradually shifting to specialized topics that enable technicians to apply their generic foundation to specific battery production scenarios.

Second, the *whom* highlights tailoring training to employees' entry-level qualifications to help new technicians quickly achieve autonomy. While all new employees require training in safety and quality assurance, a ‘one-size-fits-all’ approach is ineffective because of varying worker attributes. Instead, training programs should differentiate based on existing KSAOs. ‘Novice’ workers with little to no prior maintenance or battery production experience require full training. ‘Generalist’ workers have some experience in maintenance and/or battery production and can perform most basic maintenance tasks with targeted

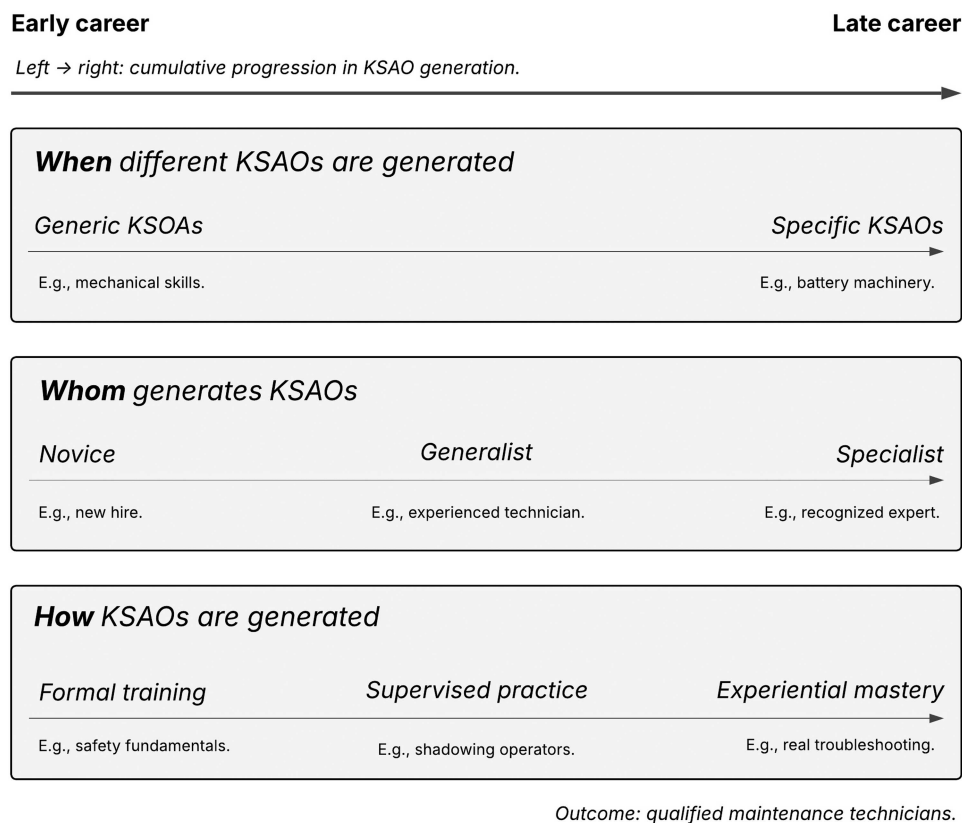


Figure 5. Training framework for maintenance technicians in battery production.

training and supervision. ‘Specialists’ workers have extensive experience in the maintenance of battery production and need minimal specific training to start working directly.

Third, the *how* emphasizes combining both theoretical and practical training elements and focusing on both on-the-job training and experience. Individual battery manufacturers naturally need to design specific training paths tailored to their own circumstances, including, e.g. theoretical courses, practical hands-on training on specialized machinery, supervision in live operative environments, and apprenticeship. This can include both conventional training formats (e.g. classroom teaching) and the use of novel digital training tools (e.g. AR glasses for task guidance, VR for hazard simulations, and digital-twin sandboxes for diagnostics), and it serves to facilitate both KSAO generation within individuals and transfer between individuals.

To make the framework more tangible, consider this illustrative example of *Novice* technicians entering a battery gigafactory, grounded in the study's empirics (Section 4). These newly hired workers, with little or no prior maintenance experience (e.g. from non-manufacturing backgrounds), begin with generic online and/or classroom training at the factory, focused on safety, process understanding, and maintenance fundamentals (e.g. handling thermal runaway). Whereas all workers learn core safety concepts, content can also vary by department (e.g. technicians in formation and ageing study cell charging and automation programming for conveyors and robots, whereas cell assembly technicians are trained to spot quality defects and learn basic chemistry owing to exposure to hazardous materials). Next, novices move into more structured on-the-job training and experience, gradually taking on routine tasks such as inspections and repairs by accompanying more skilled technicians. This is complemented by a tailored curriculum aligned with departmental needs and developmental goals, enabling a systematic progression from generic to specific KSAOs. For instance, extended electrical training is needed for formation chamber equipment, while chemical training is needed to maintain electrolyte filling machines. Training plans can also be individualized based on KSAO assessments at the start and through periodic checkpoints, and shop floor learning and experience are further reinforced through coaching and mentoring by more skilled technicians as new challenges arise in daily work. Over time, technicians gain the capacity to perform maintenance tasks independently, with their progress evaluated through, e.g. direct observations or inspections of work tasks. This stepwise training approach illustrates the framework's emphasis on sequencing (when), differentiation (whom), and integration of theory and practice (how).

6. Discussion

Using an in-depth case study in battery cell production, this study provides new insights into desired worker attributes and training for maintenance technicians. Our theoretical conceptualization of the individual-level capacity of maintenance technicians guided the empirical inquiry into desired KSAOs and the structure and efficacy of current corporate training. Specifically, the findings revealed narrative insights into technicians' experience, roles, attributes, and technological change, along with a thematic identification of 21 distinct KSAOs. We also uncovered challenges, gaps, and improvement potentials in the existing training program. Based on our findings, we developed practical frameworks that classify the identified KSAOs by specificity and content and provide guidance for designing training programs for maintenance technicians in battery production. In doing so, we make several theoretical and practical contributions.

7. Theoretical contributions

Our conceptualization of the individual-level capacity of maintenance technicians (Section 2), grounded in the KSAO concept and resulting in the conceptual framework (Figure 1), bridges existing SHRM literature (Boon et al., 2018; Marshall et al., 2024; Ployhart & Moliterno, 2011; Ployhart et al., 2014) and makes it contextualized and anchored to scholarships in industrial maintenance and LIB production. This form of theoretical contextualization (Tsang & Colpan, 2025), where SHRM literature is combined with maintenance knowledge and the LIB context, contributes to a better understanding of phenomena as well as understanding how, and how well, existing theory applies in new contexts (Venkatesh, 2025).

Specifically, our study provides a unified foundation for achieving a richer understanding and more actionable insights for human resource topics in industrial maintenance. The conceptual framework (Figure 1; including KSAO definitions, specificity, content, and mode of generation) contributes to conceptual clarity, allowing for the precise study of maintenance workers, consistency in research, and enhanced accumulation of scientific knowledge. In effect, existing research streams and worker typologies or taxonomies (Bengtsson & Berglund, 2024; Benhamza Hlihel et al., 2024; Duarte & Santiago Scarpin, 2023) can be consistently (re-)interpreted and further developed using our framework. The empirical findings on the capacity and KSAOs of maintenance technicians (Section 4, Figure 3) provide rich real-world insights into desired worker attributes in battery production. Since little is known about specific KSAOs for maintenance in this setting (Dahmen et al., 2024), our 21 identified KSAOs form the basis for a novel taxonomy of worker attributes for maintenance technicians in LIB gigafactories. Furthermore, the theoretically grounded analysis and framework classification of the 21 KSAOs (Table 2 and Figure 4) allow related research on maintenance qualifications in battery production to be consistently interpreted and aligned with established scientific concepts (Albatts, 2023).

By directly comparing our empirical KSAOs with the taxonomy in Benhamza Hlihel et al. (2024), we find that 16 out of 21 KSAOs (76%) overlap, reinforcing them as generic maintenance KSAOs (e.g. troubleshooting, communication, teamwork). The remaining five KSAOs (14%) are unique to our KSAO list and are thus domain-specific to battery production, including battery machinery, clean and dry room protocols, safety procedures, interdisciplinary thinking, and personal drive. The KSAO classification adds further granularity, e.g. by distinguishing between mechanical, electrical, and mechatronic skills rather than treating them as a single category of 'technical skills' (Benhamza Hlihel et al., 2024). A similar pattern emerges when compared to the skill card by Albatts (2023), where 16 KSAOs explicitly or implicitly overlap (e.g. maintenance processes, battery machinery, battery products, safety procedures), confirming both their generic relevance and specificity for LIB production. Notably, the five non-overlapping KSAOs emphasize the Other characteristics category (e.g. personal drive, calm mentality), highlighting how our KSAO framework captures generic, non-cognitive KSAOs. Accordingly, our primary contribution lies not in identifying entirely novel competences but in demonstrating how maintenance KSAOs can be systematically identified, classified, and strategically linked to SHRM strategies.

Nevertheless, our empirical KSAO classification is interpretive, with attributes such as adaptability, continuous learning, and teaching and learning representing borderline cases that could plausibly fit multiple categories (e.g. adaptability could also be interpreted as dispositional and falling under Other characteristics). While we classified the KSAOs based on informant expressions and our theoretical interpretations, our contribution lies less in exact attribute placement but more in demonstrating how KSAOs can be meaningfully differentiated into classes with clear implications for SHRM in maintenance (e.g. hiring and education). Thus, for maintenance scholarship more broadly, our theoretical elaborations and empirical findings provide a rigorous and generalizable base for conducting similar systematic identification and analysis of desired worker attributes for maintenance employees in other industrial sectors. This contributes to broadening the scope of potential maintenance worker attributes being studied. Furthermore, as we study the nascent context of LIB production, our findings can serve as a starting point for investigating the boundary conditions of SHRM theory in industrial maintenance contexts, such as variations in desired worker attributes and training program effectiveness in ramp-up vs. steady-state production.

Similarly, our novel empirical insights into challenges and opportunities for onboarding and training new maintenance technicians highlight the strong need for increased systematicity in generating KSAOs within maintenance organizations. While the empirics (Section 4.2) and the training framework (Section 5.2) are contextualized to battery production, the conceptual foundation on KSAO acquisition and development, including the importance of on-the-job training and experience, broadly applies to any industrial sector. This aligns with similar calls for tailored and role-specific training and mentorship structures (Tretten et al., 2025). Furthermore, the experienced shortcomings of the firm's LMS (e.g. lack of practical training and reliance on repetitive tests) relate to the limits of digital learning in hands-on occupations such as industrial maintenance (Shamsuzzoha et al., 2021). While digital training systems offer rapid, standardized education at scale, the informants revealed a mismatch with the practical and experiential nature of maintenance technicians' work. Accordingly, hands-on training, supervised practice,

and situated learning are needed to develop and demonstrate sufficient practical proficiency. Thus, our empirical findings and resulting training framework (Figure 5) support a call for more blended training models, where digital elements (e.g. gamification) complement rather than substitute practical training and development of tacit shop floor judgement (Peña, 2025). In this way, our study generates transferable insights into maintenance training that extend to other industrial settings.

Finally, this study provides a generic foundation for relating and substantiating the worker attributes of maintenance employees to productivity improvements. Since individual-level capacity and associated KSAOs are foundational predictors of performance behavior and outcomes (Marshall et al., 2024), our insights into KSAOs and training programs support continued research aiming to link the attributes of high-performance maintenance workers to not only specific operational indicators such as MTBF, MTTR, and OEE but also labor productivity more broadly.

8. Practical contributions

For industry, we offer practical KSAO and training frameworks providing clear guidance for hiring, onboarding, and training maintenance technicians. The framework (Figure 4) and associated KSAOs (Table 2) clarify which worker attributes should be prioritized in maintenance organizations. While demonstrated in battery production, the same structure can be applied in any industrial sector. The key feature for practitioners is the ability to easily identify important KSAOs, distinguish them by content and specificity, and relate them to appropriate mechanisms for KSAO acquisition and/or development.

Likewise, our identified training gaps, deficiencies, and improvement potentials (Section 4.2) emphasize the need for managers to prioritize training program development for maintenance technicians in battery production. By giving voice to the experiences of on-site workers and providing the training framework (Figure 5), we offer a blueprint for managers to design and implement training programs. While contextualized to battery production, the training framework can inspire managers in other industries seeking to develop systematic yet flexible training programs for new maintenance technicians.

8.1. Limitations

Being among the first empirical studies on maintenance technicians in the European LIB sector, there are limitations to address in subsequent research. While the single-case design enables an in-depth understanding of maintenance technicians in a novel, hard-to-access setting, it relies on three boundary conditions shaping analytical generalizability. First, the study was situated in a new venture firm entering the battery market, which may differ from incumbent battery manufacturers with more established routines and systems. Second, the Swedish national and institutional context reflects strong safety norms, formalized training expectations, and labor regulations that are likely to differ from other national contexts (e.g. the US or China). Third, the observed plant was a greenfield facility in the ramp-up stage, which may amplify the emphasis on onboarding and imply that worker perceptions and priorities evolve as production transitions to steady-state operations. Thus, our findings are most analytically generalizable to early-phase, high-growth industrial settings in developed economies. Consequently, further research should contrast and extend the findings to incumbent battery manufacturers and automakers entering battery production, and more broadly, examine the boundary conditions of SHRM theory in industrial maintenance.

To further support broader applicability and generalizability, future research would also benefit from deploying a set of complementary methodological approaches that facilitate both further depth (e.g. qualitative, longitudinal field studies) and greater breadth (e.g. quantitative surveys or experiments with statistical analysis). Analytically, we did not focus on uncovering the underlying reasons or causes of the informants' lived experiences, critically analyzing all emerging issues (e.g. why technicians expected minimal disruption from digitalization), or going in-depth in investigating the potential of digital tools to improve training programs (e.g. using XR and/or digital twins). Theoretically, we chose to engage with existing theory from the SHRM literature and thus omitted potentially relevant concepts or streams of emerging literature in production and operations management, such as human-centricity and human-machine reconciles (Choi et al., 2022; Van Oudenhoven et al., 2023). Addressing such limitations would be

a relevant starting point for future research. Furthermore, the broad use of cell manufacturing as the unit of analysis has not differentiated maintenance roles across process stages or environments (e.g. in our outside clean or dry rooms). The study also assumed sufficient labor supply, not considering current worker shortages, and validation of the proposed KSAO and training frameworks was beyond the scope of the study.

8.2. Future research directions

Our study opens up new and wider research areas to explore. We propose three core future research directions to further enhance the understanding of worker attributes and training for maintenance employees. First, the European battery industry is nascent, with most greenfield LIB production sites yet to commence full operations. Our study was conducted during the ramp-up phase, characterized by production instabilities, high process variability, and frequent product changes (Dahmen et al., 2024). Future research should explore how desired KSAOs and training programs differ across plant life cycle stages, such as steady-state production. Furthermore, since our study provides a static snapshot, future research should focus on more dynamic representations and strategies for SHRM in maintenance operations.

Second, although informants were clearly cautious about digital disruptiveness, this perception warrants careful interpretation. Our findings reflect worker experiences at a particular point in the firm's growth trajectory, and such reserved anticipation may stem from multiple sources: maintenance work being perceived as grounded in tacit, experiential, and context-specific KSAOs that are hard to codify and automate; digitalization conflicts with technicians' professional identity and legitimacy as hands-on practitioners; or perceptions of future work being extrapolated from prior, less transformative technology introductions. A key theoretical and managerial challenge is therefore to better understand how the future-of-work perceptions are formed in industrial maintenance. Such research could draw on the growing knowledge on digitalization and the future of work (Kraus et al., 2023) and examine specific impacts on shop-floor workers (Ammirato et al., 2023), such as maintenance technicians (Bengtsson & Berglund, 2024), including tasks that can be partly or fully automated (Colombari et al., 2024).

Third, the financial consequence of production delays in the LIB sector (Dahmen et al., 2024) drove the case firm's target to reduce training time for maintenance technicians. This creates a paradox: a clash between extreme pressures for rapid ramp-up and meeting production targets with the time required for on-the-job training and experience to develop maintenance technicians capable of ensuring production stability. This major challenge needs to be addressed in research, with a clear pathway involving more research on the effective use of digital technologies (e.g. XR, digital twins) for maintenance training and education (Bordegoni & Ferrise, 2023).

9. Conclusions

Motivated by the importance of maintenance for manufacturing success and concerns for inadequate labor productivity, we examined desired worker attributes and training needs for maintenance technicians. Specifically, we developed a conceptual framework encompassing the specificity, content, and mode of generation of individual-level KSAOs and conducted an in-depth case study in the emerging European battery production industry. In this novel, dynamic, and highly technical environment, we empirically identified 21 desired worker attributes for maintenance technicians and critically examined existing training. Using these findings, we developed practical KSAO and training frameworks.

Our theoretical and practical contributions relate to concept clarity and research consistency, novel insights into KSAOs and training challenges, and practical guidance for generating high-performance maintenance technicians in advanced manufacturing settings. We also offer three future research avenues concerning dynamic representation and strategies for human resource management in maintenance, the implications of industrial digitalization for the future of work for maintenance technicians, and resolving the paradox of sufficient training time whilst meeting extreme production targets. In effect, we provide a new foundation for research at the intersection of industrial maintenance and strategic human resource

management. We hope to inspire researchers to pursue this topic and contribute to scholarly and industrial developments that improve labor productivity in maintenance operations.

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Author contributions

CRedit: **Anton Pettersson:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft; **Axel Ramhult:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft; **Oscar Larsson:** Conceptualization, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing; **Jon Bokrantz:** Conceptualization, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Owing to reasons of confidentiality from the case firm, supporting data is not available.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this article, the authors used ChatGPT5 for language improvement (revising original, human-written text to improve language quality and readability, including identifying and fixing spelling and grammatical errors, inconsistencies in tone and style, and inappropriate word choice). Thereafter, the authors reviewed and edited the content and take full responsibility.

Ethics statement

This study did not obtain formal ethical approval. Such approval was not required since the nature of the research was not deemed in conflict with any relevant guidelines for research ethics (e.g. with respect to medical research involving human participants).

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Appendix A

This appendix includes full descriptive summaries of the 21 KSAOs in Table II. (K) = Knowledge, (S) = Skill, (A) = Abilities, (O) = Other characteristics.

Maintenance processes (K): a general understanding of maintenance operations and the fundamental processes is crucial for the effective application of maintenance methodologies. This includes but is not limited to work structures such as planning, scheduling, spare parts management, work instructions, documentation, and reporting. While the informants suggested minor industry-specific variations, they emphasized how these core processes remain largely consistent between battery production and other manufacturing settings.

Battery machinery (K): to perform maintenance tasks effectively, technicians need thorough knowledge of the specialized machinery used in battery production (e.g. coating or electrolyte filling). The machines used in this sector are often at the cutting edge of technology, incorporating advanced control and execution systems that require precise understanding and handling (e.g. pneumatics, measurement technology, specialized drive systems, machine elements, and tooling). Thus, the complex nature of the production equipment requires in-depth knowledge and a specialized understanding of machine functioning and performance to execute routine maintenance and perform more in-depth troubleshooting.

Battery products (K): knowledge of the electrochemical, mechanical, and thermal properties of the battery products being produced is important for maintenance technicians since machine health (e.g. degradation and calibration) can directly or indirectly influence intermediate or final quality outcomes. Thus, understanding how battery products are related to and influenced by machine function and performance is crucial for quick and effective maintenance actions, especially since technicians often need to edit the settings of machinery during or after maintenance interventions.

Clean and dry room protocols (K): since a substantial part of battery production takes place in clean and dry room environments, maintenance technicians need knowledge on how to enter in and out as well as operating in these conditions to avoid contamination. Understanding and adhering to the strict protocols in these areas (e.g. moisture), which are specifically designed to meet the exceptionally stringent requirements of battery production is crucial to avoid, for example, dust or particles from tools and spare parts compromising the sensitive electrochemical production processes.

Safety procedures (K): knowledge of safety procedures and routines is essential for maintenance technicians, as they work with a wide variety of machines and chemicals that are associated with multiple risks. Battery manufacturers require all employees to thoroughly understand and adhere to established safety guidelines. For example, this knowledge is particularly critical for maintenance tasks that risk exposure to hazardous materials such as electrolytes, where adhering to established procedures is crucial to ensuring both personal and operational safety.

Mechanical (S): mechanical skills are critical for maintenance work in battery production owing to the complexity of the machines, which rely on numerous physical and mechanically moving parts that require regular inspection, repairs, and replacements, including components such as rollers and guides, tensioners, and cutting blades. Mechanical skills to maintain these equipment systems are fundamental essentials for technicians in battery production since precise mechanical functioning (e.g. alignment) is crucial for the operation of complex machinery.

Electrical (S): electrical skills are also important for maintenance technicians, as battery production equipment incorporates advanced electrical components such as servo motors, high-voltage systems, and wiring. Thus, skills in diagnosing and maintaining such components are crucial to ensure the safe and proper functioning of sophisticated electrical systems integrated into modern battery production equipment.

Mechatronics (S): mechatronics skills are essential for maintenance technicians owing to the highly automated battery production processes that integrate mechanical, electrical, and control systems. Technicians need to be skilled in working with components such as sensors, actuators, solenoids, and PLCs to maintain, troubleshoot, and calibrate automated equipment, and this skill is vital to ensure consistent synchronization between mechanical movements and electronic controls in high-precision production processes such as coating or stacking.

Troubleshooting (S): identifying the root cause of machine failures to minimize downtime in battery production requires excellent troubleshooting skills. Maintenance technicians must therefore be proficient in diagnosing and resolving machine issues to quickly restore production. Many informants emphasized troubleshooting as one of the most important skills for maintenance technicians since it directly impacts restoration time and thus production efficiency.

Chemical handling (S): the requirements for chemical handling skills among maintenance technicians in battery production are particularly pronounced owing to the volatile and reactive nature of the materials involved. The risks associated with chemical exposure necessitate a high level of vigilance because even minor mismanagement can lead to severe accidents and operational disruptions. Maintenance technicians thus need to be skilled in carefully handling hazardous chemicals (e.g. cleaning health-endangering liquids or handling explosive gases).

Digital tools (S): using digital tools is becoming an increasingly important skill for increasing the degree of troubleshooting and maintenance of battery production machinery, and maintenance technicians are expected to be proficient in using these tools during task execution. As more digital technologies are integrated into maintenance practices, technicians need to continuously hone their skills in such tools to enhance their efficiency and accuracy in diagnosing and repairs.

Communication (S): effective communication is crucial for maintenance operations in battery production, and the informants emphasized the need for strong communication skills to support collaboration and coordination across teams and functions. For example, technicians need to be skilled in clearly conveying complex technical information to other maintenance colleagues in maintenance as well as to members of other organizational functions. Good communication skills are also valuable for driving internal alignment of maintenance best practices.

Teamwork (S): maintenance is a team effort that relies on the combined contributions of multiple individuals, roles, and functions. Maintenance technicians in battery production therefore need teamwork skills to ensure effective collaboration and prevent silo thinking. Maintenance organizations need to combine the capabilities from various parts of the organization to meet their targets, and effective teamwork skills are critical for cross-functional problem-solving, coordination during emergency downtime, and task synchronization during planned replacements.

Continuous learning (S): maintenance technicians need to be skilled in continuously improving their capabilities and developing as employees, especially to keep up with rapidly evolving technologies (e.g. remote maintenance) and processes in battery production. Digitalization will further emphasize the need for skills in continuous learning as new technologies become integrated into daily maintenance operations. Maintenance technicians must therefore be capable of swiftly learning to use new tools, techniques, and ways of working as they emerge.

Teaching and training (S): it is essential to ensure that knowledge is effectively shared and transferred among maintenance employees, for example, to prevent mistakes due to poor handover between tasks and shifts. As technologies and operational practices evolve, skills in teaching and training become important to ensure continuous employee development and the preservation of valuable and collective expertise within the entire maintenance

workforce. Maintenance technicians must therefore be skilled in passing on their knowledge to their peers, especially in such a rapidly changing landscape as battery production.

Analytical reasoning (A): the informants clearly emphasized how maintenance technicians with greater abilities of analytical reasoning are better at diagnosing breakdowns and identifying root causes in battery production machinery. They also emphasized the importance of logical thinking about how actions on one machine can impact other areas of the production line. This ability is especially pronounced when technicians need to make quick decisions in situations where specific instructions, fault code indices, or machine documentation are unavailable.

Interdisciplinary thinking (A): maintenance technicians need the ability for interdisciplinary thinking to understand the full scope of the task setting and all impacted organizational entities to make correct and safe decisions. This ability is vital for integrating various types of knowledge and information from different organizational functions and technical systems into practical problem-solving. As the production processes and associated machinery become complex by encompassing a larger scope, variety, and uncertainty (e.g. the entire gigafactory flow), interdisciplinary thinking becomes increasingly important for maintenance technicians.

Adaptability (A): maintenance technicians need to be able to adapt quickly to new situations, tools, and work structures as technology and processes evolve. The ability to adapt is essential for effectively navigating a dynamic setting such as battery production, and adaptability allows maintenance technicians to keep up with technological advancements and changing operational demands. Digitalization and increasing system complexity are expected to further exceed the need for adaptability among maintenance technicians.

Calm mentality (O): maintenance technicians in battery production are often exposed to stressful situations that require clear thinking and keeping composure under pressure. Therefore, having a calm mentality is important for technicians to cope with high-stress environments. This characteristic is especially important for staying calm and focused during problem-solving in potentially dangerous maintenance situations.

Personal drive (O): since equipment and machines in battery production can fail in numerous and often unpredictable ways, maintenance technicians cannot rely on standard processes for all potential problems that may occur. This demands a high level of personal drive among technicians to initiate and find their own solutions and take responsibility for their work. Similarly, developing proactive behavior and independent problem-solving requires maintenance technicians to be personally driven toward growth and improvements.

Strong work ethic (O): battery production is an environment characterized by rapid expansion and intense pressure to deliver. Therefore, a strong work ethic is crucial for ensuring efficient maintenance workflows and smooth collaboration between coworkers and teams. In fast-growing and multicultural companies, maintenance technicians must be susceptible to diverse approaches, including attitudes toward innovation or work routines such as tool handling, whilst at the same time meeting high expectations.