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Unravelling supply chain complexity in maintenance operations of battery production

Jon Bokrantz^a , Hafez Shurrab^b , Björn Johansson^a  and Anders Skoogh^a 

^aDepartment of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden; ^bCollege of Business Administration, Ajman University, Ajman, United Arab Emirates

ABSTRACT

Europe's emerging lithium-ion battery production sector faces immense challenges with Supply Chain Complexity (SCC). This article explores sources of and responses to SCC within maintenance operations of battery production. Using an engaged scholarship approach within automotive original equipment manufacturers (OEMs) and battery cell manufacturers in Sweden, qualitative data were collected and analysed using SCC theory. Our core findings reveal 37 sources of SCC classified by origin and type and 40 responses across four practice clusters. This study offers in-depth insights into the potential impact of SCC on maintenance operations in battery production and provides actionable guidance for managing complexity. It also identifies five future research avenues: investigating complexity interactions, matching sources and responses, exploring complexity-inducing responses, identifying internal-external interfaces and examining social aspects of SCC. In effect, the study sets the agenda for research on battery production maintenance and positions SCC as a versatile theoretical lens for understanding the emerging battery sector.

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Complexity; maintenance; production; battery; lithium-ion; supply chain

1. Introduction

The emerging battery industry has triggered a global industrial transformation and initiated unprecedented investments in manufacturing capacity for battery cells and packs. The recent industry developments are perhaps most noticeable in the automotive industry, where the demand for high-performance lithium-ion batteries (LIB) for electric vehicles (EV) is expected to grow substantially (Schmuck et al. 2018). The industrial landscape is characterized by competition between automotive original equipment manufacturers (OEMs), battery incumbents and new market entrants that also extend geopolitically. As an industry that historically did not exist much outside Asia, the developments have ignited a re-shoring trend for manufacturing capacity and supply chain diversification. In Europe (the context of this article), the scale of investments in greenfield 'giga factories' (e.g. close to 50 plants totalling close to 2 TWh capacity are announced by 2030¹) underscore the determination to build up a new industry that business leaders and policymakers consider vital for reaching net-zero industry goals and ensuring future competitiveness.²

Against the backdrop of global developments, our research impetus came from automotive OEMs and new market entrants within Europe's emerging LIB sector. Managers and engineers involved in planning, scaling and operating cell manufacturing and pack assembly plants expressed a

range of complications with Supply Chain Complexity (SCC) (C. C. Bozarth et al. 2009; Shurrab and Jonsson 2023) within maintenance operations. SCC is a comprehensive lens encompassing the entire value-creating process (e.g. planning, sourcing, making and delivering) and recognizing the permeable boundaries between internal operations and external environments (Ateş et al. 2022). This holistic view facilitates a nuanced understanding of interconnected complexity challenges that arise from internal operations as well as external issues of supply and demand (Fernández Campos, Trucco, and Huaccho Huatuco 2019; Serdarasan 2013). Practitioners' current and anticipated SCC for maintenance in battery production included but was not limited to the numerous geographically dispersed equipment suppliers, the diversity of production processes and the vast array of dedicated machinery and equipment. This raised substantial concerns since complexities in internal operations and external network connections can significantly impact the frequency, recovery time and severity of disruptions (Bode and Wagner 2015; Craighead et al. 2007; Guntuka, Corsi, and Cantor 2023) and aggravate the ability to meet sustainability targets (De Stefano and Montes-Sancho 2023). The negative effect of SCC on operational performance is well-documented (Ateş et al. 2022), and SCC is widely perceived as one of the most pressing challenges in modern supply chains (e.g. Bode and Wagner 2015; Chand et al. 2022; Turner, Aitken, and Bozarth 2018).

CONTACT Jon Bokrantz  jon.bokrantz@chalmers.se

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Since effective complexity management is rare in practice (Gerschberger et al. 2023), SCC within maintenance operations poses a significant risk to battery manufacturers' ability to achieve desired performance levels. Complexity arising from internal processes along with external and intra-organizational dependencies is a major cause of low process stability and high rejection rates in battery production (Abramowski et al. 2023; Wessel et al. 2023). While real-world data from the emerging battery industry is scarce, the estimated cost of lost production during the scaling period of a 50 GWh greenfield battery plant can be upwards of \$4 million per day, where around 50% of the capacity losses can be attributed to machine downtime (Breiter et al. 2022). Industry experts project that maintenance improvements in battery production can reduce downtime-related costs by up to 10%.³

Through an engaged scholarship approach (Van de Ven 2007), our research utilizes the lens of SCC to address these complexity concerns in maintenance operations of battery production. By doing so, we make three main contributions to the bodies of knowledge on SCC, maintenance operations and battery production: (1) We unravel SCC in a novel empirical context and shed light on the challenges of maintenance operations in the emerging battery sector. Furthermore, (2) we dissect structural and dynamic SCC across various operational environments (demand, internal and supply) and provide rich insights into the factors shaping maintenance operations. Lastly, (3) we identify a comprehensive set of management practices for effectively responding to SCC, followed by developing a practical framework for complexity management in maintenance. In effect, this article pioneers a research trajectory for maintenance operations in battery production and positions SCC as a versatile theoretical lens for understanding the emerging battery sector.

2. Theoretical background

2.1. Battery production

The demand for LIBs is skyrocketing as major automotive markets accelerate the transition towards EVs. For example, McKinsey & Company estimates a 30% growth in battery demand and a ten-fold increase in battery value chains by 2030.⁴ This expected demand surge has sparked an unprecedented level of investments in battery production capacity, where three leading players compete: incumbent battery manufacturers expanding their portfolio, automotive OEMs seeking to support their EV transition and new market entrants.

Battery research has a long history with more than 50 years of R&D on materials compositions (e.g. nickel, manganese, cobalt), battery designs (e.g. chemical, electrical and physical properties) and individual manufacturing techniques (e.g. stacking) (Zhang et al. 2020). A battery pack consists (in principle) of cells stacked in modules, electrically connected and controlled by cooling and a battery management system. LIB is the (current) key technology used for EVs, where the cells are in themselves electrochemical systems

consisting of an anode, cathode, separator, electrolyte and housing (Väyrynen and Salminen 2012).

The fundamental production processes for LIBs originated in the 1990s for consumer electronics, and the process know-how is now being transferred and scaled to large-format LIBs for EVs (Kwade et al. 2018). In principle, cell manufacturing consists of (1) *electrode production* (active materials are mixed, coated, dried and compacted onto metal sheets for anodes and cathodes), (2) *cell production* (cutting, stacking and inserting electrodes into cell housings with electrolyte) and (3) *cell finishing* (activation of cells through cycles of charging, discharging and resting). Module and pack assembly consists of (1) *module assembly* (sorting, stacking and joining cells into modules) and (2) *pack assembly* (integrating modules, cooling and control systems into the final pack housing) (Schmuck et al. 2018). However, research progress for battery production at scale is lacking (Liu et al. 2021), where emerging research streams with relevance to operations and production management include (but are not limited) to cost and resource modelling (Nelson et al. 2015; Wood, Li, and Daniel 2015), quality management (Schnell et al. 2019; Schnell and Reinhart 2016; Westermeier, Reinhart, and Zeilinger 2013) and technology management (Kampker et al. 2012; Lee et al. 2010; Wessel et al. 2023).

Complexity is a severe performance threat in LIB production. Battery production is characterized externally by a reliance on a diverse range of specialized raw materials and manufacturing equipment, each subject to its supply chain challenges and geopolitical considerations (Brinn 2022). Furthermore, the rapid evolution of battery technologies requires frequent changes in production processes and materials, adding to the complexity of supply chain management (Jones et al. 2022). Therefore, a deep understanding of how external factors can influence battery production is needed for success (Wessel et al. 2023).

Internally, the inherent features of battery production processes and dedicated machinery contribute to this complexity (Abramowski et al. 2023; Schnell and Reinhart 2016). Cell manufacturing combines converging and diverging energy and material flows, single-unit and batch processes and continuous and discrete-part production in the same system (Turetskyy et al. 2020). As noted by Westermeier, Reinhart, and Steber (2014), the production chain for LIB cells involves a multitude of diverse and partially time-dependent processes, encompassing over 20 distinct steps and involving more than 250 different machine parameters across various processes such as chemical, mechanical, thermal and electrochemical operations. Such intensity and diversity create a complex network of relationships and unpredictable impacts on product quality, amplifying the susceptibility to supply chain disruptions and demanding a higher level of coordination and control than many other manufacturing industries (Schreiber et al. 2022). Moreover, the precision required in the production process, coupled with stringent quality control standards, introduces additional complexity (IEA 2022), often resulting in low processing yields and prolonged ramp-up times (Wessel et al. 2023).

LIB production also presents a range of specific challenges for maintenance. The combination of continuous and discrete-part production processes requires maintenance teams to manage a wide variety of equipment and technologies (Kwade et al. 2018; Schreiber et al. 2022). These challenges are further compounded by the greenfield nature of most battery factories, which demands navigating the complexities of new production system ramp-ups while scaling maintenance operations (Despeisse et al. 2023). The demand for high precision, cleanliness and adherence to stringent quality standards puts additional pressure on maintenance activities (Kwade et al. 2018; Westermeier, Reinhart, and Steber 2014). Moreover, the economic and safety implications of unplanned downtime can be substantial, requiring precision in maintenance decisions to prevent lost production and severe repercussions such as fires and exposure to hazardous materials (Duffner et al. 2021; Väyrynen and Salminen 2012).

Despite these complexities and the critical role of maintenance in LIB production, specific research on maintenance is almost non-existent. Most studies focus on analytical cost models designed to estimate the total manufacturing costs of LIBs under various conditions, typically treating maintenance as a negligible overhead (Duffner et al. 2021). While general literature on battery production sheds some light on maintenance-related challenges, e.g. the requirement for fast response times to solve production faults (Wessel et al. 2023), detailed knowledge about the specific maintenance needs of battery production remains scarce and is often kept confidential within companies (Westermeier, Reinhart, and Steber 2014). This underscores the need for targeted research to address the complexity concerns in maintaining battery production systems.

2.2. Supply chain complexity

Complex systems defy mechanistic structures; their behaviours are not simply the sum of their parts, eluding straightforward predictions (Anderson 1999). This notion is rooted in systems theory and linked to the seminal complexity definition of Simon (1962), describing it as 'a system that includes a large number of varied elements that interact in non-simple ways' (p. 468). This definition resonates within the operations and supply chain management community. As a broad concept, complexity has been an enduring topic in this discipline for decades (e.g. Bode and Wagner 2015; C. C. Bozarth et al. 2009; Vachon and Klassen 2002) and continues to be an important domain for academic research and industrial applications (Birkie and Trucco 2016; Cantarelli 2022; Robson, Ojiako, and Maguire 2024; Soliman and Abreu Saurin 2022). With a specific focus on supply chain management, Ateş et al. (2022) described SCC as 'the extent to which the supply chain of an organization is made up of a large number of varying elements that interact in unpredictable ways' (p. 3).

Despite the emphasis on 'supply chain' in the SCC term, it is important to recognize that the concept is not limited to supply issues. The SCC literature emphasizes a holistic view of complexity that encompasses both operational issues

within manufacturing facilities and external factors of demand and supply in the business environment, as well as their interconnections. For example, C. C. Bozarth et al. (2009) recognizes the internal characteristics of manufacturing plants as key elements of SCC, (Ateş et al. 2022) uncover product and process-related complexity as main themes in a recent meta-analysis and (Turner, Aitken, and Bozarth 2018) discusses many responses that consist of internal operations practices. This view also reflects a wider interpretation of supply chain management as encompassing all functions and processes related to the management of supply chains and the transformation of inputs to outputs, including operations, logistics, purchasing, etc. (Bokrantz and Dul 2023). Our study adopts this recognized and broad perspective on SCC.

SCC research is often approached from a positioning perspective, focusing on the elements of complexity, such as the diversity and number of entities (e.g. suppliers and customers) (Gunasekaran, Subramanian, and Rahman 2015) and the depth or geographical spread of the supply chain structure (Costantino and Pellegrino 2010; Sharma et al. 2020). Supply chains also, by nature, exhibit characteristics that are not immediately discernible from their individual elements, where these chains produce non-linear interactions and intricate cause-effect patterns that make SCC notoriously challenging to navigate (Chand et al. 2022; Fernández Campos, Huaccho Huatuco, and Trucco 2022; Gligor, Russo, and Maloni 2022). For example, the intertwined nature of complexity can produce hidden and varying effects on capacity utilization, demand fulfilment, inventory levels (Chatha and Jalil 2022), recovery from disruptions (Guntuka, Corsi, and Cantor 2023) and resilience (Iftikhar et al. 2022). Although the elements of SCC interact in multifaceted ways that add layers of challenges for organizations (Ennen and Richter 2009), some firms can harness it to achieve operational excellence, showcasing the potential of complexity as both a hurdle and a boon (Gerschberger et al. 2023).

Unravelling SCC in a dynamic context such as battery production, which is characterized by novelty and limited knowledge, requires a streamlined theoretical approach. This article, therefore, focuses on aligning with and contributing to two main streams of research and ongoing discourses on SCC: (1) sources of complexity (Ateş et al. 2022; Bode and Wagner 2015; Serdarasan 2013) and (2) responses to complexity (Aitken, Bozarth, and Garn 2016; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Huaccho Huatuco et al. 2021).

2.2.1. Sources of complexity

Understanding the sources of SCC is crucial for effective management (Shurrab and Jonsson 2023). As defined by Serdarasan (2013), a source of complexity refers to 'any property of a supply chain that increases its complexity' (p. 534), representing the foundational elements of SCC. The literature classifies these sources into two main dimensions: type and origin.

Type refers to *the way* the sources are generated (Serdarasan 2013), and it is widely acknowledged that SCC can be segmented into two dimensions: *structural complexity*

and *dynamic complexity* (Fernández Campos, Huaccho Huatuco, and Trucco 2022; Iftikhar et al. 2022). Structural complexity (also known as detail complexity) refers to the 'distinct number of components or parts that make up the system' (C. C. Bozarth et al. 2009) (p. 79) and is manifested in two core attributes: *numerousness* (i.e. the number of elements in the system) and *variety* (i.e. heterogeneity among the elements in the system) (Ateş et al. 2022; Bode and Wagner 2015). An additional attribute of structural complexity that is recognized in the literature but has received less attention is interconnectedness (i.e. structural links or dependencies between the elements in the system) (Afini Normadhi et al. 2019; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Gerschberger et al. 2012; Serdarasan 2013; Vachon and Klassen 2002). Dynamic complexity relates to 'the unpredictability of a system's response to a given set of inputs' (C. C. Bozarth et al. 2009) (p. 79) and is reflected in the two core attributes of *unpredictability* (i.e. the inability to predict future states of the system accurately) and *uncertainty* (i.e. lack of complete knowledge or information about the system) (de Leeuw, Grotenhuis, and van Goor 2013; Dittfeld, Scholten, and Pieter Van Donk 2018; Turner, Aitken, and Bozarth 2018; Vachon and Klassen 2002). Additional attributes linked to dynamic complexity are time, speed, pace, change, volatility, randomness, motion and noise (Ateş et al. 2022; de Leeuw, Grotenhuis, and van Goor 2013; Fernández Campos, Huaccho Huatuco, and Trucco 2022; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Serdarasan 2013; Shurrab and Jonsson 2023).

Structural and dynamic complexity encompasses both technical and social features (Ateş and Luzzini 2023), such as the number and variety of products and decision-making conflicts (Serdarasan 2013). In the extant literature, technical aspects of SCC have received the most extensive attention. While social and behavioural aspects are increasingly recognized (Ateş and Luzzini 2023), the technical nature of the maintenance discipline drives a predominant research focus on the inherent engineering complexity of machinery and equipment (Matyas et al. 2017; Vrignat, Kratz, and Avila 2022).

Complexity origin refers to *where* the sources are generated, which can be either internal or external to the focal organization (Iftikhar et al. 2022; Serdarasan 2013). Internally, complexity can arise within the confines of a manufacturing facility, such as products and processes (C. C. Bozarth et al. 2009). Externally, complexity can be induced by various factors that emerge from the demand environment, such as market regulations, or the supply environment, like supplier relationships (Huaccho Huatuco et al. 2021; Shurrab and Jonsson 2023). Thus, the span of SCC origins is broad, ranging from domestic complexities like political or socio-economic factors (Starr 1984) to the structural elements of the supply base (Delbufalo 2022) and product configurations (Salvador, Chandrasekaran, and Sohail 2014).

Thus, the extant literature generally seeks to provide explanations and predictions for SCC in a given context by characterizing the nature of complexity and tracing the origins of complexity. However, there is no consensus on

whether to categorize sources of SCC using type and origin as a classification scheme (Aitken, Bozarth, and Garn 2016; Serdarasan 2013; Shurrab and Jonsson 2023) or to separate the constitutive elements of SCC ('dimensions') from the underlying factors that drive them ('antecedents') (Ateş and Luzzini 2023). In this article, we adopt the former approach and seek to uncover properties that increase SCC and classify them according to type and origin.

SCC influences a variety of business functions (Ateş et al. 2022), and the unit of analysis in empirical studies includes any part of an organization that directly takes part in supply chain activities, i.e. planning, sourcing, making and delivering (Fernández Campos, Trucco, and Huaccho Huatuco 2019), including a focus on functions such as purchasing, logistics, warehousing, or production. To the best of our knowledge, no comprehensive SCC study has focused on the maintenance function, despite the widely held conjecture that production equipment and machinery have become more complex over time (Matyas et al. 2017; Vrignat, Kratz, and Avila 2022) and that empirical studies have linked increasingly complex manufacturing systems to more advanced maintenance practices (Lazim et al. 2013; Swanson 2003). From an SCC perspective, maintenance scholars have only recognized some individual sources of complexity, such as variety in production technologies and uncertainty in the technical expertise of maintenance staff (Marquez and Gupta 2006). The technical nature of the maintenance discipline is also a driver of the predominant research focus on the inherent engineering complexity of machinery and equipment.

2.2.2. Responses to complexity

Addressing the myriad challenges of complexity requires a multifaceted approach. As the detrimental impacts of SCC on operational performance are well-documented (e.g. Ateş et al. 2022; Chand et al. 2022; Heim, Peng, and Jayanthi 2014; Vachon and Klassen 2002; Wiengarten et al. 2017), organizations must employ explicit strategies to manage observed or anticipated SCC. That is, responding to complexity (Maylor and Turner 2017).

Research on responses to complexity generally seeks to provide practicing managers with a structured understanding of the available response mechanisms and support the selection of correct responses to the specific SCC faced by the organization (Aitken, Bozarth, and Garn 2016). Initially, this stream of research focused on uncovering specific responses that can be applied in practice. Examples include the use of integrated information systems with customers and suppliers, logistics outsourcing (Perona and Miragliotta 2004), reducing the number of products, increasing collaboration with supply chain partners (Serdarasan 2013), direct interaction between production and marketing and increasing visibility into plant inventory levels (Aitken, Bozarth, and Garn 2016). Thereafter, research efforts moved towards the development of more complete frameworks. Turner, Aitken, and Bozarth (2018) developed a framework grounded in the two core approaches for responding to SCC: reducing the complexity faced by the organization (i.e. 'reduction') or increasing the organization's capacity to handle it (i.e. 'accommodation').

The framework supports managers in considering the SCC faced by the organization (SCC type) and choosing responses from three categories of practices (planning and control, relational, flexibility), contingent on the nature of complexity (deleterious vs. beneficial) and nature of the response (exploitation vs. exploration).

Seeking to advance this line of research on reduction and accommodation as generic approaches for complexity management, Fernández Campos, Trucco, and Huaccho Huatuco (2019) developed a richer and more detailed framework to support practitioners in selecting suitable responses from four clusters of practices: (1) variety-reducing, (2) confinement and decoupling, (3) coordination and collaboration and (4) decision support and knowledge generation. A practice is broadly referred to as 'the methods, techniques, and tools managers implement to reduce the adverse effects of complexity in their organization' (p. 613), and a cluster is 'a bundle of practices that rely on the same principle or logic to manage complexity' (p. 615).

Huaccho Huatuco et al. (2021) developed a framework for specifically responding to complexity transfer (i.e. manufacturing organizations transfer complexity from or to their suppliers and customers) using four organizational configurations (equilibrium, source, sink, boom or burst). Recently, Ateş and Luzzini (2023) reviewed the SCC literature and proposed two main approaches: designing and moderating. Whereas designing consists of reducing (e.g. supply base rationalization) or increasing SCC (e.g. choosing suppliers from diverse backgrounds), moderating SCC consists of mitigating or leveraging using three types of practices: (1) control (e.g. contracting), (3) coordination (e.g. vendor-managed inventory) and (3) collaboration (e.g. buyer-supplier relations).

The evolving nature of complexity management, as evidenced by the diverse frameworks and approaches, necessitates an adaptive and comprehensive model that can cater to the dynamic complexities of modern supply chains. The framework by Fernández Campos, Trucco, and Huaccho Huatuco (2019) is particularly fitting for our study as it encapsulates a broad spectrum of complexity management strategies while at the same time providing granular insights into specific practices. The comprehensive and practice-oriented nature of the framework also resonates with our research impetus and empirical setting as it allows for seeking simultaneous insight into both the general mechanisms (i.e. broad categorization of approaches and practices) and specific mechanisms (i.e. detailed identification and explanation of specific practices). The four clusters of practices are briefly described below.

Variety-reducing practices reduce the degree of complexity that must be coped with by rationalization, i.e. focusing on a narrower range of elements, or standardization, i.e. establishing commonalities among elements and thus reducing internal diversity (Fernández Campos, Trucco, and Huaccho Huatuco 2019). One example is limiting product ranges and maintaining flexible production capacities to adhere to delivery schedules (Huaccho Huatuco et al. 2021). The emphasis on rationalization and standardization within the variety-reducing practices acknowledges the critical need for

simplification in complex supply chains, aligning well with contemporary managerial challenges.

Confinement and decoupling practices narrow the range of activities that must cope with complexity by focusing on the dependencies and relations between elements. Confinement aims to contain complexity within a reduced domain where specialized resources can be leveraged, and decoupling seeks to lessen the relations between elements and render certain parts of the system more independent from others (Fernández Campos, Trucco, and Huaccho Huatuco 2019). For instance, acquiring advanced production technology and understanding pricing factors (Starr 1984) or optimizing supply chain design (Gunasekaran, Subramanian, and Rahman 2015).

Coordination and collaboration practices make the organization more capable of coping with complexity by allowing employees to understand the effects of their actions outside their own domain and managing complexity more holistically, sharing knowledge and solutions, as well as synchronization and alignment between teams and functions internally and externally (Fernández Campos, Trucco, and Huaccho Huatuco 2019). These practices highlight, for example, the importance of transparency and continuous monitoring to enhance visibility and preparedness (Gunasekaran, Subramanian, and Rahman 2015; Ponomarov and Holcomb 2009).

Decision support and knowledge generation practices increase the organization's ability to cope with complexity by enhancing decision-making. Decision support practices allow employees to filter out and focus on a reduced number of decisions or provide employees with more valuable information on to base their decisions, and knowledge generation practices help employees build and maintain relevant skills and knowledge (Fernández Campos, Trucco, and Huaccho Huatuco 2019). For example, the increasing accessibility and performance of emerging digital technologies for decision support (e.g. Internet of Things and machine learning) enable intricate and continuous monitoring (Gunasekaran, Subramanian, and Rahman 2015; Iftikhar et al. 2022).

The framework's inclusive approach, addressing both strategic and operational aspects of SCC, demonstrates its suitability for organizations seeking comprehensive solutions to the dynamic challenges of modern supply chains. While all of the frameworks' practices are potentially valuable, their effectiveness may also be moderated by other factors, such as business continuity plans at the plant level (Guntuka, Corsi, and Cantor 2023) or cost considerations and risks across domestic and international markets (C. Bozarth, Handfield, and Das 1998; Lockström 2007; Trent and Monczka 2002). Therefore, navigating and addressing the challenges of SCC requires careful strategic planning where distinct complexity sources need to be matched with specific responses.

2.2.3. Conceptual framework

Figure 1 consolidates the two major streams of research on sources and responses to SCC into an integrated conceptual framework. On the left side of Figure 1, the sources are captured by the two dimensions of complexity type (dynamic complexity reflected in uncertainty and unpredictability; structural complexity reflected in numerousness and variety)

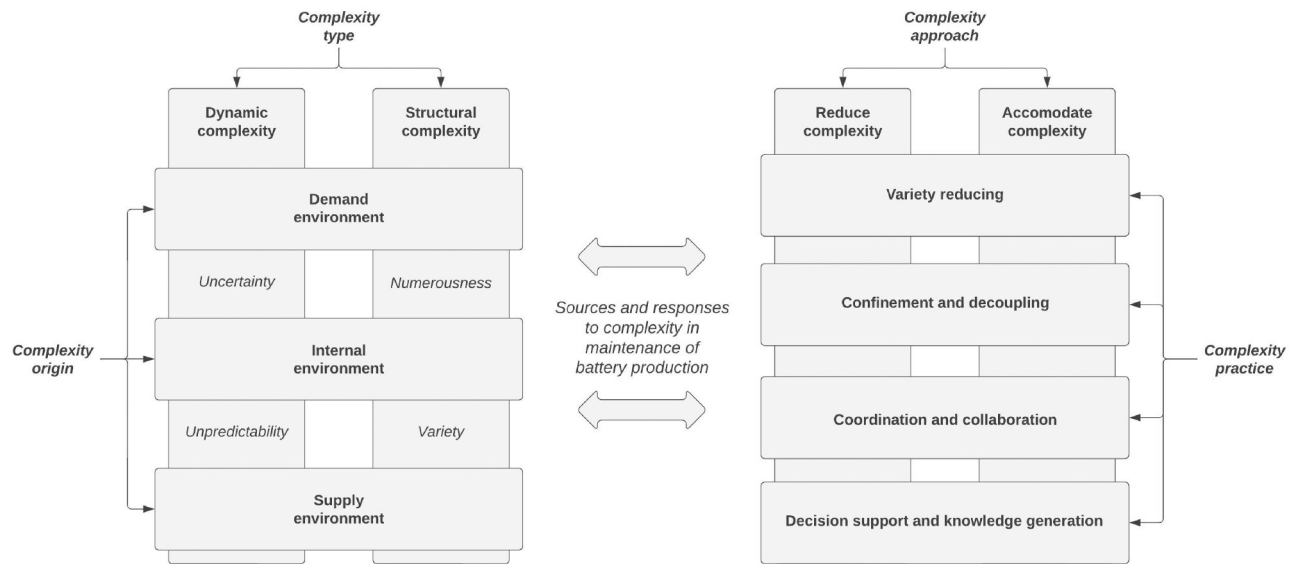


Figure 1. Conceptual framework of sources and responses to SCC in battery production maintenance.

and complexity origin (demand, internal, supply environment), which allows for effectively identifying and classifying important elements of SCC (Bode and Wagner 2015; C. C. Bozarth et al. 2009; Serdarasan 2013). To address SCC, the righthand side of Figure 3 guides the selection of responses by capturing the available management options along the two dimensions of complexity approach (reduce or accommodate) and complexity practice (four clusters of practices) (Aitken, Bozarth, and Garn 2016; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Turner, Aitken, and Bozarth 2018). The conceptual framework thus provides a holistic structure for interpreting prior SCC research and framing our study's theoretical and empirical scope. That is, our inquiry seeks to unravel the sources of complexity (type and origin) that influence maintenance operations in battery production and identify a set of responses (approach and practice) for effectively managing complexity in maintenance.

3. Research approach

LIB production represents a new phenomenon in Europe, and maintenance of battery production is a topic that has attracted little (if any) empirical research or formal theorizing to date. In instances where nascent industries emerge without substantial empirical or theoretical groundwork, there is a need for a methodological orientation that aims to shed light on new phenomena (Edmondson and McManus 2007) and anticipate new problem domains that need to be understood from a theoretical point of view and have immediate relevance for practicing managers (Corley and Gioia 2011). This positioning aligns with the exploratory stream of SCC studies that identify sources and responses to SCC in novel contexts (Shurrah and Jonsson 2023). Thus, our research approach sought to provide a deeper understanding of maintenance operations in the emerging battery sector through the lens of SCC.

3.1. Empirical setting

This study was executed in Sweden, a country that aims to be a forerunner in battery production. An entirely new industry sector is now being established from the ground up, marking one of the most significant new industrial investment projects in Swedish history.⁵ Several battery factories (cell manufacturing and pack assembly) are in various stages of planning, construction and operation across different Swedish regions, representing the focal plants of this study (see details in Section 3.2). These developments will make LIBs one of Sweden's largest export industries, and Sweden is projected to become one of the leading European countries in battery production capacity.⁶ Other existing actors with small-scale production of battery packs for offroad vehicles and stationary storage, incumbent manufacturers of nickel-cadmium battery cells, as well as sub-suppliers to LIB production (e.g. anode and cathode material) were not within the scope of the study.

3.2. Research design

With the ongoing industrial development of greenfield battery factories, it became imperative to connect with key organizational informants, observe the evolving systems and interact with those who are designing, building and operating them. We, therefore, took inspiration from *engaged scholarship*, a collaborative research approach that leverages the distinctive knowledge of both scholars and practitioners (Van de Ven and Johnson 2006). The engaged approach, where researchers and industry professionals collaborate closely (Van de Ven 2007), has recently been used to study various emerging operations topics such as drones in logistics applications (Maghazei, Lewis, and Netland 2022), hybrid digital manufacturing of metal components (Stark et al. 2023) and smart services using condition-based maintenance (Akkermans et al. 2024). We adopted three core research design elements of engaged scholarship (Van de Ven 2007). First, we established a *collaborative learning community*

consisting of maintenance managers and engineers from automotive OEMs and battery cell manufacturing firms, together with researchers in operations management and industrial engineering (detailed in Table 1⁷). Second, our inquiry spanned an extended period of 16 months, from January 2022 to May 2023, allowing for a comprehensive understanding from diverse stakeholders. Third, we utilized multiple methods such as group discussions, site visits and focus groups to obtain rich, in-depth qualitative data (detailed further in Section 3.3). An overview and timeline of the research process are shown in Figure 2, illustrating the collection of methods used, their time of execution (in terms of quarter of the year) and the resulting qualitative database.

Our unit of analysis was the manufacturing firm. At the time of the study, the battery factories within each firm were in different life-cycle stages. In the automotive OEMs, one cell manufacturing plant was in the engineering phase (Start of Production [SOP] 2030), one pack assembly plant was in the commissioning phase (SOP 2023), and one pack assembly plant was in the engineering phase (SOP 2025). In the battery cell manufacturing firm, the plant was in the operating phase (SOP 2021). We sought to recruit practitioners from the respective firms that represent agents that directly face SCC (left side of Figure 1), are active in the planning, development and implementation of responses to SCC (right side of Figure 1), or possess strategic insights about existing or anticipated SCC in their respective firm (both sides of Figure 1), thereby enabling a collective understanding of the maintenance of

battery production at different organizational levels. The agents (Table 1) included maintenance managers who held major decisional roles and possessed critical knowledge of the firm's strategic priorities and maintenance engineers who possessed domain knowledge and were immersed in the daily work of design, construction and operations of green-field battery factories. The community was further enriched by leveraging relationships with practitioners (e.g. quality engineers), researchers (e.g. material science), educators (e.g. vocational training) and policymakers (e.g. country councils). Second, our inquiry spanned an extended period of 16 months, from January 2022 to May 2023, allowing for a comprehensive understanding from diverse stakeholders. Third, we utilized multiple methods such as group discussions, site visits and focus groups to obtain rich, in-depth qualitative data (detailed further in Section 3.3).

3.3. Methods for data collection

Exploring new phenomena requires employing a variety of empirical techniques, such as interviews, group meetings, conversations, communication logs, or company document reviews (Edmondson and McManus 2007). A set of such techniques are commonly practiced in exploratory SCC studies, including, but not limited to, interviews, observations during plant tours, review of internal documents and information

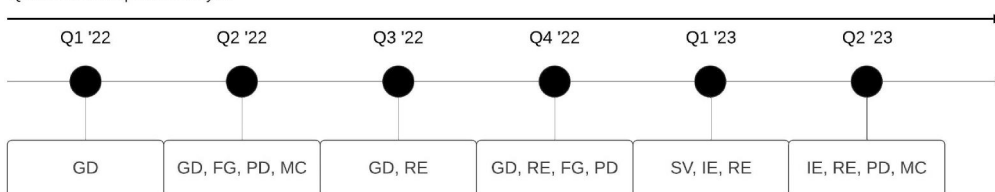
Table 1. Collaborative learning community.

Orientation	Positions	Key expertise in learning community	n	%
Automotive OEM (heavy vehicles) ^a	Maintenance manager, maintenance engineer, research manager	Managing technology, development and engineering in maintenance. Designs and implements technology use and maintenance ways of working.	4	31%
Automotive OEM (passenger vehicles) ^a	Maintenance manager, maintenance engineer, maintenance improvement leader	Managing centralized maintenance development and engineering. Designs IT infrastructures, work processes and education and training in maintenance.	3	23%
Battery cell manufacturing ^b	Maintenance manager, production engineer	Managing maintenance and facilities. Develops, implements and scales maintenance organizations (incl. all roles, tasks and processes).	2	15%
Academia	Professor, senior researcher, PhD student	Research in maintenance operations and technology development for maintenance engineering, e.g. predictive maintenance.	4	31%

^aAutomotive firms entering battery production to support their EV transition, including cell manufacturing and pack assembly.

^bNew market entrant with manufacturing of battery cells for EVs and energy storage.

Empirical timeline
Jan 2022 - May 2023
Q refers to which quarter of the year



Methods for data collection of primary data

GD = group discussion
FG = focus group
SV = site visit
IE = industry event
RE = research event

Methods for increasing trustworthiness

PD = Peer debriefing
MC = Member checking

Qualitative database
41 pages in 11-size,
single-spaced text
(14502 words)

Figure 2. Overview of the research process.

from web pages (Dittfeld, Scholten, and Pieter Van Donk 2018; Shurrab and Jonsson 2023).

We collected qualitative data from both primary and secondary sources, focusing on uncovering specific topics, issues and challenges concerning the maintenance of battery production. The scope and boundaries of our data collection were based on the conceptual framework (Figure 1), i.e. seeking to capture potential sources of SCC (structural and dynamic complexity in demand, internal and supply environment) as well as responses to SCC (practices for reducing or accommodating complexity) linked to the focal firms in our study (Table 1). To both reveal more about the phenomenon and unlock theoretical insights, we explicitly sought to collect and combine a multitude of both verbal and non-verbal data (Hansen et al. 2023).

Three main methods were used to collect *primary* data from within the collaborative learning community: group discussions ($n=16$), site visits ($n=4$) and focus groups ($n=1$) (GD, SV and FG in Figure 2).⁸ Initially, the group discussions used an open-ended format in the early phases of the research process, evolving to semi-structured formats as the research progressed. The site visits (cell manufacturing and pack assembly plants) consisted of factory tours where we made field observations and interacted with both blue- and white-collar workers. Data from the group discussions and site visits were collected through comprehensive notes. The focus group design was inspired by the procedures reported by Bokrantz et al. (2020) and was conducted with eight participants from the learning community who first submitted individual, anonymous responses ($n=73$) to a single open-ended question ('What do we need to know about maintenance of battery production?'), followed by group discussions to probe and elaborate on the responses (audio recorded and transcribed). In addition, we attended industry and research events (presentations and panel discussions) about battery production (IE and RE in Figure 2), which further enriched our understanding and data collection and helped verify specific challenges that manufacturers are facing. Besides, these events allowed for opportunistic follow-up discussions and interviews with firm representatives on key issues. Data were documented as notes. By the end of the process, our primary database extended over 41 pages in 11-size, single-spaced text (14,502 words). We also compiled *secondary* data from company presentations (e.g. PowerPoint slides), news articles, equipment vendor material and public reports (e.g. policy and business reports). These sources were collected via attendance at the industry and research events and web searches and further illuminated the emerging battery industry.

3.4. Methods for data analysis

Our analytical strategy was abductive, i.e. beginning with a set of 'rules' and our 'observations' and then inferring our 'explanations' by appraising the rules in light of the observations (Mantere and Ketokivi 2013). The advantages of an abductive strategy include the straightforwardness and replicability of the analysis, consistency with existing theory and

transparency in the analysis process (Ketokivi and Mantere 2010). These elements are essential for exploratory research on SCC in emerging industries such as battery production. We used the conceptual SCC framework in Figure 1 as the starting point ('rules'). We engaged in an iterative analysis process consisting of identifying critical issues in the data and grouping raw excerpts into codes, followed by categorizing the codes into representative and distinct conceptual entities ('observations'). We then interpreted and classified each conceptual entity as a source of complexity or response to complexity vis-à-vis the SCC framework ('explanations').

Specifically, each conceptual entity in the data interpreted to represent a source of SCC was classified according to both its origin (i.e. demand, internal, or supply environment) and type (i.e. structural or dynamic) (left side of Figure 1) (C. C. Bozarth et al. 2009; Serdarasan 2013). We also specified the theoretical domain of the sources, i.e. whether they applied to cell manufacturing and/or pack assembly. Similarly, each conceptual entity in the data representing a response to SCC was classified according to the seven specific management mechanisms derived from Fernández Campos, Trucco, and Huaccho Huatuco (2019) clusters of practices framework (i.e. standardization, rationalization, decoupling, confinement, coordination, collaboration, decision support, or knowledge generation) as well as its management approach (i.e. reduce or accommodate) (Turner, Aitken, and Bozarth 2018) (right side of Figure 2). When a conceptual entity signalled an overlap in the classification scheme (e.g. the possibility of being interpreted as both structural and dynamic complexity), we erred in the direction of distinctiveness and classified the sources and responses into their primary category. In effect, each row in Tables 2 and 3 represents a coded, classified and theoretically interpreted conceptual entity from the data.

During our analysis, all data types (verbal and non-verbal) were considered equally important and capable of informing theory (e.g. interview data and observational notes) and our abductive reasoning focused more on the researchers' interpretation rather than specific data elements (e.g. informant quotes) (Hansen et al. 2023). A focus on the effective integration of diverse data types into sets of coherent theoretical explanations was considered a powerful approach to achieving a comprehensive understanding of maintenance operations in battery production (Maxwell 2012; Patton 2014). Thus, the findings (Section 4) focus on our abductive interpretations rather than highlighting specific quotes or informant stories (Hansen et al. 2023).

Due to its exploratory nature, our analysis did not seek to differentiate between specific and general facets of SCC. That is, we strived to identify any source and response to SCC that apply to the maintenance of battery production (cell manufacturing or pack assembly), including those that may be unique to this industry (i.e. specific) as well as those that may also apply to other industries (i.e. generic). This strategy is grounded in how the SCC literature posits that SCC can often be identified and described generically while at the same time being adapted specifically to certain industries

Table 2. Sources of structural and dynamic complexity in maintenance operations of battery production.

Origin	Source	Type	Explanation	Domain
Demand environment	Regulatory development	Dynamic	Uncertainty surrounding local and global regulatory developments in a rapidly emerging battery sector, including factors such as electrical safety within maintenance.	C, P
	Technology development	Dynamic	Uncertainty stemming from continuous technological advancement and corresponding standardization, impacting the demand for new technology, skills and processes within maintenance.	C, P
	Sustainability focus	Dynamic	Uncertainty in political and corporate strategies concerning sustainable production, particularly Europe's focus on green batteries pressures maintenance organizations to minimize carbon footprint, e.g. traceability of maintenance-related information in digital product passports for cells and packs.	C, P
Internal environment	Scaling speed	Dynamic	Unpredictability in the feasibility, timing and cost of scaling up plant operations and associated maintenance processes, including ramp-up challenges such as running-in of new equipment.	C, P
	Production performance targets	Dynamic	Uncertainty in performance targets from production due to changes in market conditions and system states; setting the criteria for performance management of the maintenance organization, e.g. downtime limits and response times.	C, P
	Shop floor labour skill	Dynamic	Uncertainty in the proficiency of the workforce operating and interacting with equipment, causing human errors and subsequent equipment issues for maintenance to resolve.	C, P
	Institutional heritage	Dynamic	Uncertainty about incorporating institutional heritage into novel maintenance operations, such as the transfer of best practices when automotive OEMs transition into battery production.	C, P
	Equipment quality	Dynamic	Unpredictability in production uptime due to insufficient equipment quality, resulting in unplanned breakdowns.	C, P
	Equipment novelty	Dynamic	Uncertainty in equipment performance owing to the lack of legacy and experience with specific machinery.	C
	Equipment requirements	Dynamic	Uncertainty about equipment requirement specifications from a maintenance perspective, including e.g. safety, functionality and accessibility.	C
	Machine-product dependencies	Dynamic	Unpredictability about the influence of machine condition on intermediate and final battery quality (e.g. vibration or alignment) within and across production phases.	C, P
	Machine-machine dependencies	Dynamic	Unpredictability about structural, economic and stochastic dependencies among machines in the production flow and the associated impact on downtime propagation.	C, P
	Process speed	Dynamic	Unpredictability in maintenance planning and scheduling due to short cycle times and high takt times.	C, P
	Plant scale	Structural	Numerousness in the total responsibilities of maintenance stemming from economies of scale (e.g. site size and degree of vertical integration).	C
	Process diversity	Structural	Variety of continuous and discrete-part production processes to maintain, including e.g. active material preparation, slurry mixing, coating and stacking.	C
	Process interdisciplinarity	Structural	Numerousness and variety of disciplines involved in production machinery to maintain, including chemical, mechanical and electrical operations.	C
	Process precision	Structural	Numerousness and variety in process and machine capabilities to satisfy quality requirements, including e.g. geometrical tolerances and electrochemical properties.	C, P
	Automation levels	Structural	Numerousness and variety of automated equipment, processes and systems in production that require precision in maintenance diagnosis, inspections and repairs.	C, P
	Cleanliness	Structural	Numerousness and variety of protocols and routines for maintenance activities to comply with operating requirements in clean and dry room environments, such as cell assembly.	C, P
	Capital intensity	Structural	Numerousness and variety in economic considerations of maintenance due to significant direct and indirect costs as well as unrealized revenue from system downtime.	C, P
	Plant safety	Structural	Numerousness and variety of routines and protocols in maintenance activities due to safety hazards and chemical exposure, with little margin and large consequences for human errors.	C, P
	Equipment volume	Structural	Numerousness in the amount of production equipment to maintain, e.g. large number of stacking machines or industrial robots.	C, P
	Components and spares	Structural	Numerousness and variety of machine components and associated spare parts to be inventoried.	C, P
	Maintenance data	Structural		C, P

(continued)

Table 2. Continued.

Origin	Source	Type	Explanation	Domain
Supply environment	Maintenance tasks	Structural	Numerousness and variety of maintenance-related data to be collected and stored, including e.g. event data, sensor data and maintenance records.	C, P
	Organizational diversity	Structural	Numerousness and variety of maintenance policies and associated tasks required to ensure equipment reliability and availability.	C, P
	Labour market volatility	Dynamic	Variety of internal and external organizational units and associated personnel with whom maintenance staff interact.	C, P
	Labour market scarcity	Dynamic	Uncertainty in local and global competition for maintenance labour within the growing battery sector and associated labour movement from adjacent sectors.	C, P
	Geographical spread	Dynamic	Uncertainty in the local and global supply of qualified maintenance labour in constrained labour markets.	C
	Buyer-supplier culture	Dynamic	Uncertainty surrounding dispersion and distance in global equipment supply chains, including costs, communication barriers and risk of supply disruptions.	C
	Order lead times	Dynamic	Uncertainty in cultural sensitivity in international buyer-supplier relationships of equipment such as power balances and institutional practices.	C
	Local supplier development	Dynamic	Unpredictability in supplier lead times and availability of equipment and associated spare parts and consumables for maintenance.	C
	Supplier requirements	Dynamic	Uncertainty surrounding local supplier market developments, such as new establishments of machine vendors or maintenance service providers.	C
	Maintenance-related information	Dynamic	Uncertainty in defining maintenance requirements for equipment due to limited knowledge of supplier behaviour.	C, P
	Buyer-supplier transfer restrictions	Dynamic	Uncertainty surrounding incomplete or unreliable equipment and maintenance information, e.g. availability of technical documentation, manuals and spare parts list.	C, P
	Supplier selection risks	Dynamic	Unpredictability concerning supplier safeguard mechanisms for the transfer of technology and knowledge related to equipment and maintenance, limiting organizational learning within maintenance.	C, P
	Supplier base	Dynamic	Uncertainty to the maintenance implications of sourcing decisions for production equipment, including geopolitical risks and selection of maintenance-intensive and substandard machinery.	C, P
		Structural	Numerousness in the minimum number of equipment suppliers capable of covering the entire process chain for battery production.	C, P

(Dittfeld, Scholten, and Pieter Van Donk 2018; Perona and Miragliotta 2004).

3.5. Methods for trustworthiness

We deployed two main techniques to strengthen the confidence in the results and the trustworthiness of our analysis (see Figure 2): (1) *peer debriefing* (i.e. presenting and discussing emergent ideas and findings with colleagues not directly involved in the study and reflecting on their critical feedback) (Corley and Gioia 2004) and (2) *member checking* (i.e. having members of the collaborative learning community to react on the findings and act as judges of the credibility and consistency of our interpretations) (Lincoln and Guba 1985). These techniques were iterated throughout the research process to facilitate continuous revision and clarification of codes, categories and classifications. The two coders also continuously deployed *negotiated agreements* (i.e. discussing and debating discrepancies in coding and interpretation until an agreement is reached) (Campbell et al. 2013). At the end of our research process, we observed signals of saturation in the form of repetition of information at

the first-order level and confirmation of existing conceptual entities at the second-order level (Suddaby 2006). However, given the nascent character of the phenomenon, reaching full saturation and completely fleshing out the conceptual domain of maintenance of battery production was neither deemed feasible nor consistent with the exploratory nature of the study.

4. Findings

The following sections present our findings on sources of SCC (Section 4.1) and responses to SCC (Section 4.2). The main empirical findings are presented in Tables 1 and 2, consisting of all identified and classified sources and responses to SCC and their theoretical explanations. While the tables capture the core empirical and theoretical details, we also provide complementary summaries of the findings in the corresponding text. Owing to our abductive analysis strategy and the fact that our qualitative data consisted of a variety of verbal and non-verbal data treated with equal importance, the presentation of findings focuses on our theoretical interpretations rather than highlighting specific data elements (e.g. interview quotes) (Hansen et al. 2023).

Table 3. Responses to complexity in maintenance operations of battery production.

Response type	Response practice	Management mechanism	Explanation	Management approach
Variety reducing	Accelerating employee onboarding	Standardization	Standardized introduction programs with defined materials and processes for training that effectively and efficiently guides new maintenance employee into the details of their jobs, including, e.g. understanding battery production, maintenance tasks and safety procedures.	Reduce
	Systematizing clean room maintenance	Standardization	Standardized routines for maintenance in clean room environments, including, e.g. task identification, task analysis, development of procedures, documentation, monitoring and continuous improvement.	Reduce
	Developing early equipment management	Standardization	Standardized processes for early equipment management of battery production equipment in procurement, including formalized procedures for defining equipment requirements and design for maintainability.	Accommodate
	Streamlining maintenance data structures	Standardization	Standardized structures, architectures and routines for collection and storage of maintenance-related data (e.g. sensor data and maintenance records), including e.g. completeness, consistency and accessibility.	Reduce
	Limiting data scope	Rationalization	Limiting the range of collected and stored maintenance-related data to prevent information overload by defining and focusing on critical data points that are essential for maintenance decision-making.	Reduce
	Formalizing organizational design	Rationalization	Formalizing the organizational structure of the maintenance function to limit the line of command, e.g. by streamlining communication channels, simplifying the hierarchy and reducing the number of formal roles. Potentially resolved by copying organizational structures for maintenance from conventional automotive plants.	Reduce
Confinement and decoupling	Defining competencies and roles	Confinement	Defining clear roles and competence profiles for maintenance employees (e.g. engineers and technicians) to ensure effective task-skill matching at the level of individuals.	Reduce
	Identifying unique maintenance skills	Confinement	Identifying the distinct and unique maintenance skills that are specifically required for battery production, ensuring the presence of necessary expertise and allowing for adaptation to changes and advances in the dynamic battery sector.	Reduce
	Classifying equipment criticality	Confinement	Design and implementation of equipment criticality classification system that allows for assigning maintenance priority (e.g. response and monitoring) to the most critical equipment, thereby confining maintenance operations within manageable boundaries.	Reduce
	Specifying maintenance programs	Confinement	Developing defined maintenance programs (i.e. how and what) for all production equipment (e.g. stacking machines) in different production sectors (e.g. electrode production), allowing for focused management of maintenance task execution.	Reduce
	Implementing autonomous maintenance	Decoupling	Relieving some of the workloads from the dedicated maintenance personnel by decoupling routine maintenance tasks and independently allocating them to machine operators (e.g. cleaning, inspection).	Reduce
	Establishing a local supplier base	Decoupling	Establishing a reliable local supplier base for maintenance-related needs, including, e.g. equipment, spare parts, consumables and contractors, thereby allowing for isolating and managing specific elements of the maintenance process more independently	Accommodate
	Protecting vulnerable spare parts	Decoupling	Identifying critical spare parts that are susceptible to supplier disruptions and isolating and mitigating risks by managing them more separately.	Accommodate

(continued)

Table 3. Continued.

Response type	Response practice	Management mechanism	Explanation	Management approach
Coordination and collaboration	Separating cross-industry knowledge transfer	Decoupling	Separating the development of unique (i.e. context-specific) and universal (i.e. generic) maintenance practices and adopting proven best practices from existing and similar industries (e.g. automotive, pulp & paper, chemistry and medicine).	Reduce
	Differentiating employee mentoring	Decoupling	Addressing the lack of battery production experts for conventional in-house mentorship by separating workforce development into internal (e.g. development and acquisition) and external (e.g. contracting or alliances), thereby increasing access to specialized knowledge and training opportunities.	Accommodate
	Training for supplier separation	Decoupling	Actively educating and training maintenance execution suppliers and contractors in specific areas of required maintenance expertise, allowing specific maintenance tasks to be separated and transformed into services.	Accommodate
	Rebalancing employee mix	Coordination	Constrained by a limited pool of experienced maintenance workers in early operative phases, the initial employee mix (novice majority) can be rebalanced over time (expert development) by strategically investing in, e.g. talent acquisition, training and development programs.	Accommodate
	Fostering equipment experts	Coordination	Assigning dedicated teams of maintenance workers that undergo comprehensive education and training in specific equipment types (e.g. stackers), allowing for the development of specialized knowledge, the ability to allocate larger responsibility for maintenance strategy development to experts and rapid problem-solving during unplanned downtime.	Accommodate
	Scheduling maintenance tasks	Coordination	Procedures for scheduling maintenance tasks (i.e. when and whom) for all equipment in the plant (e.g. inspections, replacements), including coordination with production schedules to minimize downtime.	Reduce
	Establishing routines	Coordination	Streamlining maintenance operations by establishing routines, responsibilities, information flows, work order management and organization ownership, thereby enabling relevant and timely delivery of information, consistent and correct maintenance execution and prompt resolution of unplanned downtime.	Reduce
	Designing maintenance workshops	Coordination	Designing and arranging physical maintenance workshops, including both central workshops (e.g. equipped with advanced tools and staffed with skilled workers) and satellite workshops (e.g. close to the production lines with essential tools and technicians that address routine maintenance needs), thereby minimizing transportation of materials and tools and simplifies task coordination.	Reduce
	Developing data-driven work	Coordination	Development of data-driven work processes that leverage analytics to identify patterns in historical and real-time data, allowing for the prediction of equipment failures and prescription of suitable maintenance tasks.	Accommodate
	Ensuring knowledge resilience	Coordination	Creating organizational resilience against high employee turnover (e.g. loss of trained experts) by establishing mechanisms for knowledge transfer, documentation and succession planning.	Accommodate
	Coordinating cross-functionally	Coordination	Synchronizing planning and scheduling between maintenance and other functions and making joint decisions (e.g. production, engineering, IT, quality)	Accommodate
	Collaborating cross-functionally	Collaboration	Establishing relationships between maintenance and other functions (e.g. production, engineering, IT, quality) that include sharing of data, information and knowledge	Accommodate

(continued)

Table 3. Continued.

Response type	Response practice	Management mechanism	Explanation	Management approach
Decision support and knowledge generation	Building equipment supplier relations	Collaboration	Developing and deepening strategic relationships with critical battery production equipment vendors in global supply chains, allowing for precise and fast information sharing, priority handling of critical parts and rapid problem-solving.	Accommodate
	Involving maintenance in procurement	Collaboration	Active involvement of maintenance employees in strategic procurement to align procurement decisions with maintenance needs and requirements, thereby ensuring a closer fit between procured production equipment and viable maintenance practices.	Accommodate
	Combining data sources	Decision support	Leveraging and combining multiple data sources (e.g. internal and add-on sensors) to provide a more comprehensive understanding of machine health and performance, thus enabling the provision of actionable insights from pattern identification and failure predictions.	Accommodate
	Exploring new data sources	Decision support	Exploring and exploiting new types of data that are rarely used in conventional maintenance decision-making (e.g. vision cameras for inspection or novel sensors) allowing for more accurate equipment monitoring and more precision in decision-support systems.	Accommodate
	Unravelling maintenance-quality relationships	Decision support	Uncovering the relationships between observable machine health parameters (e.g. vibration or alignment) and the quality of produced batteries, thereby revealing critical knowledge that maintenance teams need to effectively manage, control and improve equipment functionality and performance.	Accommodate
	Developing decision-support tools	Decision support	Developing tailor-made decision-support tools and methods (e.g. AI solutions for specific equipment) that maintenance employees can effectively use to make informed and precise decisions about maintenance planning, scheduling and execution.	Accommodate
	Uncovering machine interactions	Decision support	Uncovering machine interactions in battery production flows allows for extracting and explicating dependencies that govern possibilities for maintenance planning and scheduling with minimal impact on production (e.g. maintenance opportunity windows).	Accommodate
	Providing shop floor cognitive support	Decision support	Developing cognitive support tools on the shop floor to provide simple, easy and immediate access to information about machine status (e.g. machine visualizations and dashboards), thus enabling maintenance employees to quickly assess and respond to changing machine conditions and safety concerns.	Accommodate
	Specifying controllable equipment parameters	Decision support	Identifying directly observable and controllable equipment parameters that impact the production process (e.g. humidity, temperature), allowing maintenance teams to proactively make machine adjustments that ensure optimal process conditions and minimize the risk of deviations.	Accommodate
	Recruiting employees	Knowledge generation	Diversifying the maintenance workforce through recruitment from both local and global labour markets as well as from both within sectors (i.e. battery production) and across sectors (i.e. similar types of production), thereby allowing for finding and acquiring talent that ensures the necessary know-how within the maintenance function.	Accommodate
	Transfer employees internally	Knowledge generation	Transferring and up-skilling existing maintenance employees from conventional automotive production to battery production within the same firm, thereby leveraging the existing internal talent pool and facilitating the effective relocation of employees who bring their prior knowledge and experience into battery production.	Accommodate

(continued)

Table 3. Continued.

Response type	Response practice	Management mechanism	Explanation	Management approach
	Cultivating firm-specific expertise	Knowledge generation	Implementing strategies and processes that encourage maintenance employees to deepen their understanding and commitment to firm-specific systems and processes, thereby ensuring a long-term supply of competence by retaining employees with valuable and specialized maintenance skills.	Accommodate
	Acquiring knowledge and skills in purchasing	Knowledge generation	Developing the necessary knowledge and skills for global equipment supplier relations, e.g. the ability to understand cultural nuances, communication styles and business practices, thereby allowing maintenance experts to interact, negotiate and collaborate with equipment suppliers effectively.	Accommodate
	Training and educating workers	Knowledge generation	Systematic worker education and training to equipment maintenance employees with essential knowledge and skills required to perform maintenance tasks safely and effectively (e.g. process and product understanding, safety hazards), empowering them to make informed decisions and contribute to the overall quality of the maintenance process.	Accommodate
	Innovating new training formats	Knowledge generation	Developing new and innovative training formats and procedures such as digital training with simulation, augmented reality, or virtual relation (especially targeting pre-operational training), thereby providing maintenance employees with immersive and practical learning experiences that facilitate the acquisition of necessary skills.	Accommodate

4.1. Sources of complexity

Table 2 presents the findings of sources of complexity that influence the maintenance of battery production and their classification according to origin and type. We identified a total of 37 sources of structural ($n = 14$, 38%) and dynamic complexity ($n = 23$, 62%). The majority of the sources originate from the internal environment ($n = 23$, 62%) and the supply environment ($n = 11$, 30%), with few sources identified in the demand environment ($n = 3$, 8%). Whereas all 37 sources apply to cell manufacturing (C), 17 also apply to pack assembly (P). The sources reflect a variety of technological, organizational and human challenges that are all of prominence and deserve attention from scholars and practitioners.

From the demand environment emerges complexity reflecting the battery sector's dynamism. Absent regulatory frameworks, such as those tied to safety in electrical installations, add uncertainty to both local and global developments. Rapid technological advancements in battery products and production techniques introduce uncertainties in maintenance, affecting skillsets, process standardization and new engineering tools. Our findings also highlight the distinct European emphasis on sustainability, underscoring the importance of control and reduction of carbon footprint expected from every player in the battery production ecosystem, including maintenance organizations. Political and corporate strategies for sustainable battery production translate into pressure on maintenance to minimize emissions and waste in both production and maintenance processes.

The internal environment presents multifaceted challenges. Technologically, the vastness of manufacturing plants

means maintenance must handle diverse production processes, a vast equipment range and enormous maintenance data. Organizational challenges involve handling internal policies and maintenance tasks while ensuring coordination among various internal and external entities. All organizational routines must also be put, scaled and kept in place at extraordinary speed. Here, new market entrants have more freedom to innovate their maintenance practices, while automotive OEMs are more likely to be bound to standard practices and prior institutional views. The human factor is also a significant source of uncertainty, such as how the proficiency of shop floor personnel influences the potential for human errors and equipment issues when interacting with machinery. In addition, additional pressure on maintenance is driven by the high stakes and demands on production targets, precision in processes, cleanliness requirements and machine capabilities to satisfy stringent quality parameters related to, e.g. geometrical tolerances and electrochemical properties. Maintenance functions must also ensure a higher level of precision in inspections, diagnosis and repairs in fully automated production that runs with short cycle times and fast takt times. Economic and safety considerations from unplanned downtime have substantial financial ramifications in terms of direct and indirect costs and potential revenue losses, and maintenance decisions need to be balanced against the severe repercussions of mishaps, such as fires and exposure to hazardous material.

In the supply environment, we find sources of complexity that have become focal pain points in the growth of the European battery sector. One of the most pressing problems

is labour market uncertainty, with fierce local and global competition for maintenance labour and a shortage of skilled workers, pulling skilled individuals from adjacent sectors. European machinery suppliers for cell manufacturing are virtually non-existent, leading to uncertainties in global equipment supply chains related to, e.g. defining and communicating machine requirements across language borders, as well as anticipating supply distributions that affect lead times and availability of essential spares and consumables for maintenance. Access to technical documentation, e.g. detailed manuals and spare parts lists, also introduces uncertainty and is often constrained by supplier-sharing restrictions and lack of translation. Discrepancies in maintenance-relevant information can easily lead to operational issues and downtime. At a higher level, this type of restriction in technology and knowledge is reflected in extensive safeguarding. Battery production equipment is currently in a phase where everything is proprietary and suppliers keep their cards close to their chests. Restrictions not only protect intellectual property but also directly influence the rate and depth of organizational learning within maintenance. Uncertainty in the extent to which valuable knowledge is shared or withheld can profoundly impact the ability of maintenance functions to adapt, innovate and improve. In extension, the supplier selection choices are not merely about short-term transaction costs but also carry long-term maintenance implications. These decisions introduce considerable uncertainty and risk. For instance, geopolitical risks can influence the stability and reliability of machinery and spare parts supply chains. Similarly, opting for the purchase of machinery that is maintenance-intensive or substandard can severely amplify maintenance challenges down the line.

These uncertainties are further compounded by cultural dynamics in international buyer-supplier relationships and limited insights into supplier behaviour and predictability, which require careful navigation of power balances, institutional practices and cultural sensitivity. At the same time, as local markets evolve, new vendors and maintenance providers will emerge, reshaping the supply landscape. This boils down to ensuring (in the short and long runs) a minimum number of equipment suppliers and associated maintenance services capable of holistically covering the entire process chain for battery production. Thus, for Europe to emulate Asia's dominant vertically integrated battery sector, manufacturers must establish a comprehensive network of equipment suppliers and maintenance services, crafting their ecosystem.

4.2. Responses to complexity

Table 3 presents the findings of responses to complexity in the maintenance of battery production and their classification according to the clusters of practices and associated management mechanisms and approaches.

The findings reveal 40 responses to complexity across the four clusters of practices: variety reducing ($n=6$, 15%), confinement and decoupling ($n=10$, 25%), coordination and collaboration ($n=11$, 27%) and decision support and knowledge generation ($n=13$, 33%). The management mechanism

with the most responses was coordination ($n=8$, 20%), followed by decision support ($n=7$, 18%) and decoupling and knowledge generation ($n=6$, 15%, respectively). A majority of the responses aim to accommodate complexity ($n=26$, 65%) compared to reducing complexity ($n=14$, 35%).

Standardization practices include defined programs and materials for training, formalized maintenance routines and processes, structured data collection and storage and rationalization practices seeking to limit the range of collected maintenance data and lines of command in the hierarchy to prevent information and communication overload. These responses primarily serve to reduce complexity by variety-reduction, specifically by limiting diversity and establishing commonalities among information, routines and processes.

Focusing on the interdependencies and relationships between system elements, we identified confinement practices that pinpoint distinct skills, competencies and roles for maintenance workers. These practices also define equipment criticality and specific maintenance programs for different production phases, facilitating prioritization of various maintenance needs for equipment and machinery. Such reduction-oriented responses seek to contain complexity within a reduced domain and tackle it with specialized resources. To render parts of the system more independent from others, we uncovered decoupling practices such as cultivating local suppliers and protection mechanisms for critical spare parts. These serve as de-risking or safeguard mechanisms against constraints and disruptions in supplier relations. We also discerned practices that seek to untangle and structure the system into smaller independent pieces, including the separation of channels for knowledge transfer, employee mentoring and supplier training. Collectively, these practices allow for narrowing the range of activities that must cope with complexity.

To facilitate synchronization and alignment both within maintenance teams and between other functions, we identified coordination practices like the systematization of routines and scheduling, repair workshop designs and data-driven work processes. Furthermore, to foster knowledge sharing in a broader domain, we identified related practices, including balancing the employee mix, developing internal equipment experts and ensuring knowledge resilience against employee turnover. Since the full scope of complexity cannot be solely managed within the maintenance function, we identified collaboration practices that seek to manage complexity jointly through shared processes and solutions, such as establishing cross-functional relations, involving maintenance in procurement and nurturing supplier relationships. Broadly, these practices accommodate complexity by broadening the domain of capability of maintenance teams and managing current issues more holistically, internally and externally.

Finally, we identified decision-support practices that aim to capitalize and visualize extant data and information from equipment, unravelling hidden and unknown maintenance-quality relationships and machine interactions and specifying distinct and controllable equipment parameters. These practices provide maintenance employees with technological solutions that augment or automate decision-making. We also

identified various knowledge-generation practices aiming to build up human capital resources within the maintenance function. These involve recruiting, transferring and retaining skilled workers as well as supporting employees in acquiring and maintaining relevant competencies. Collectively, this pool of responses ultimately seeks to increase the maintenance organization's ability to cope with complexity by elevating the cognitive abilities of humans, both with and without supporting technology.

5. Discussion

Through an engaged scholarship approach within the emerging European battery sector, this study provides the first deep and rich insights into SCC that influence the maintenance of battery production. Specifically, our empirical findings reveal numerous sources (stemming from demand, internal and supply environment) and types (structural and dynamic) of SCC and several corresponding responses representing four clusters of practices (variety reducing, decoupling and confinement, coordination and collaboration and decision support and knowledge generation). These findings have a range of theoretical and practical implications.

5.1. Theoretical implications

Our findings provide novel insights into the unexplored area of maintenance of battery production. By unravelling SCC in the battery industry, we draw attention to the dynamics embedded in this future-critical sector and learn about complexity in a novel context. Adopting a broad interpretation of SCC allowed for capturing a wide range of interconnected complexities that span both internal operations and external issues of demand and supply. This holistic view provides a more comprehensive and nuanced understanding of complexity in maintenance operations, which is particularly valuable in an emerging and rapidly evolving industry such as battery production where the boundaries between internal operations and the external environment are often blurred. Thus, framing our study and findings through a broad SCC lens effectively shapes a diverse academic discourse and agenda for future research.

By identifying both sources of SCC (Table 2) and responses to SCC (Table 3), we provide insight into the nature of SCC (Ateş et al. 2022; Bode and Wagner 2015; C. C. Bozarth et al. 2009) as well as relevant practices for managing SCC (Aitken, Bozarth, and Garn 2016; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Turner, Aitken, and Bozarth 2018) in maintenance operations of battery production. Theoretically, this contributes to a foundational understanding of sources and responses to SCC that apply to maintenance operations in cell manufacturing and pack assembly plants. While many of the identified sources and responses are predominantly operational in nature, this is consistent with the broader interpretation of complexity. This view indeed offers distinctive insights into the interaction between internal operations and the broader business environment, including how operational decisions

ripple through the entire supply chain and vice versa, as well as the critical role of internal decisions and processes in managing complexity that originates externally.

Being the first study to comprehensively use SCC theory as a lens to understand maintenance operations, we also provide a holistic perspective on complexity in maintenance more broadly. Grounding maintenance research in the full SCC lens serves to drastically enlarge the scope of complexity beyond individual sources, such as the engineering complexity of components, machinery, equipment and production technologies (Marquez and Gupta 2006; Matyas et al. 2017; Vrignat, Kratz, and Avila 2022). A full SCC lens also serves to expand research that targets the alignment of more advanced maintenance practices to increasingly complex manufacturing systems (Lazim et al. 2013; Swanson 2003) towards capturing increasingly complex business environments. This study improves the conditions for accelerating such developments.

As this study sought to capture both specific and generic features of SCC (Dittfeld, Scholten, and Pieter Van Donk 2018), many of the sources and responses may also apply to maintenance operations in other industries. For example, while the theoretical explanations in Tables 2 and 3 are grounded in the specifics of the battery industry (columns 'explanation'), the abstraction into general categories (columns 'sources' and 'response practice') also allows for understanding SCC in maintenance operations of industries facing similar challenges. For example, our findings can serve as the foundation for research that links the challenges of the battery industry to the broader phenomenon of rapidly scaling greenfield operations.

To SCC research more broadly, our study extends the theoretical domain of SCC theory (i.e. the universe of instances for which the theory is expected to hold) by applying it in a novel way to maintenance operations. By using SCC theory to analyse the maintenance function in battery factories specifically, we effectively extend the explanatory and predictive value of complexity theory to support processes such as maintenance that are often overlooked and by many seen as necessary but non-value-adding activities needed to sustain the business. In addition, by synthesizing, contrasting and structuring the existing literature on both sources and responses to SCC into a unified conceptual framework (Figure 1), we contribute with theoretical refinement (Fisher and Aguinis 2017). Specifically, the framework provides a coherent structure for analysing the nature of SCC (complexity type and origin) and the scope of viable response mechanisms (complexity approach and practice), allowing researchers to distinguish between different complexity sources and responses more easily. Our study then effectively showcases how the framework can be used to identify, structure and contrast a large pool of sources and responses to SCC from empirical data sets. In effect, this supports scholars in making transparent, repeatable and replicable inferences that contribute to building a larger and more coherent body of knowledge on SCC.

5.2. Practical implications

Our findings provide substantial guidance to maintenance practitioners seeking to design and implement strategies for managing SCC, an effort whose importance is widely acknowledged by scholars and practitioners (Ateş et al. 2022). Strategic management of complexity is a process that consists of identifying current or anticipated SCC (Bode and Wagner 2015) and taking actions to address SCC (Turner, Aitken, and Bozarth 2018), spanning from the early phases of system design and development to full-scale operations. To support this process, we synthesize our findings into a framework for practitioners to holistically understand and deal with SCC in related maintenance operations (Figure 3).

The framework follows the tradition in SCC research to provide practitioners with actionable insights into the complexity faced by the organization and support the selection of appropriate responses (Aitken, Bozarth, and Garn 2016; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Maylor and Turner 2017; Turner, Aitken, and Bozarth 2018). Given that the exploratory nature of this study permits primarily an overarching and high-level consideration of SCC among maintenance practitioners, in combination with the fact that the effectiveness of any complexity management approach hinges on each organization's prerequisites and objectives (Turner, Aitken, and Bozarth 2018), the framework seeks to support industrial firms in initiating a more in-depth analysis of sources and responses to SCC in their respective organizations. Specifically, the framework is intended to be used by maintenance managers in battery factories as guidance to raise a series of questions together with their internal teams of engineers, leaders and technicians to generate a shared understanding of current or anticipated complexity and agree on what responses to implement. This enables maintenance organizations in battery factories to carefully choose methods, tools and techniques for SCC that are aligned with their own business strategy (Aitken, Bozarth, and Garn 2016).

First, to identify sources of SCC (left side of Figure 3), practitioners are advised to utilize the descriptions in Tables 2 and 3 to recognize important facets of current or anticipated SCC that may be generated from any of the three different origins (*i.e. where does SCC stem from?*) and types (*i.e. which way is SCC shaped?*). This helps not only to adopt a holistic view of SCC (Aitken, Bozarth, and Garn 2016) but also to prioritize the most essential sources (Bode and Wagner 2015) specific to their own organization. Second, to address SCC (the righthand side of Figure 3), they are advised to choose a viable set of responses in Table 3 that are adequate for the identified sources of SCC in their own organization (Turner, Aitken, and Bozarth 2018). Possible managerial responses (*i.e. how to manage SCC?*) fall on a spectrum: on one end, reduction-oriented practices focus on reducing structural complexity, and on the other, accommodation-oriented practices emphasize handling dynamic complexity. Maintenance organizations in battery factories can effectively tackle the challenges of complexity by using specific responses across the full spectrum (*i.e. what practices mitigate SCC?*), matching the proper responses with identified complexities. Such matching entails implementing methods, tools and techniques to reduce the adverse effects of SCC (Fernández Campos, Trucco, and Huaccho Huatuco 2019). Adopting this approach would counteract the prevalent issue where effective management of SCC is seldom integrated into corporate agendas (Ateş et al. 2022) and rarely (if ever) into maintenance strategies.

In contrast to existing frameworks for managing SCC that seek to support the supply chain function (Fernández Campos, Trucco, and Huaccho Huatuco 2019), business units (Aitken, Bozarth, and Garn 2016), or project teams (Turner, Aitken, and Bozarth 2018), our framework is for maintenance organizations. Even though many sources and responses to SCC may be the same or similar for various types of organizations at a higher abstraction level, the framework (Figure 3) and the associated descriptions (Tables 2 and 3) provide the

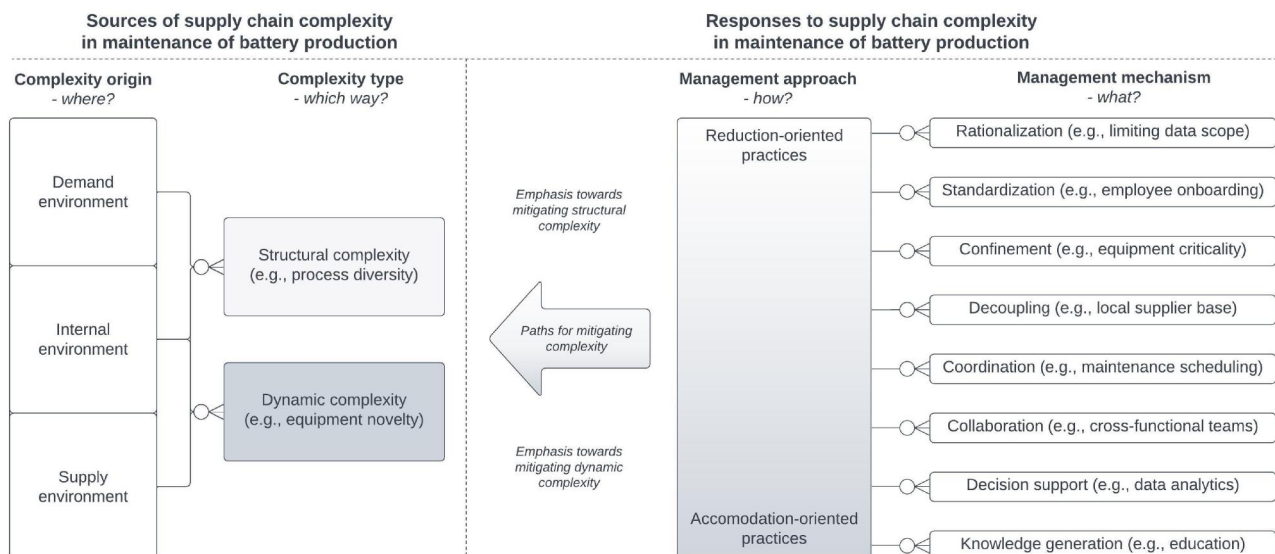


Figure 3. Framework for supply chain complexity in maintenance operations of battery production.

necessary nuances for managing SCC specifically in maintenance operations of battery production.

5.3. Future research directions

Against the backdrop of our empirical findings and theoretical and practical implications, we propose five future research directions for the maintenance of battery production as well as SCC more broadly.

First, as our findings revealed various sources of structural and dynamic complexity, it is natural that the next step is to focus on *complexity interactions* (Shurrah and Jonsson 2023). That is, how the individual sources interact in space and time (e.g. buffering or amplification) to aggregate and shape the total SCC of maintenance of battery production and influence performance outcomes. As the sources do not operate in isolation and contribute linearly to higher levels of SCC (Fernández Campos, Huaccho Huatuco, and Trucco 2022), future research could theorize and empirically test vertical (across origins for each type), horizontal (across types for each origin) and diagonal interactions (across origins and types) (Dittfeld, Scholten, and Pieter Van Donk 2018).

Second, developing better practical advice for selecting responses to complexity requires a deeper understanding of *sources-responses matching*, i.e. choosing the practices that are adequate for managing specific sources of SCC (Fernández Campos, Trucco, and Huaccho Huatuco 2019; Turner, Aitken, and Bozarth 2018). This requires additional research that specifies and tests the effectiveness of matching pairs or bundles of sources and responses in terms of their performance implications (Sousa and Voss 2008), represented in our findings by the pool of sources (Table 2) and responses (Table 3). This research direction also provides a natural extension from the exploratory and qualitative nature of this study towards more explanatory and quantitative research, such as testing the impact of SCC on various metrics of maintenance performance (e.g. unplanned downtime) and the extent to which specific responses can mitigate such consequences.

Third, while existing SCC research predominantly posits that responses are designed to either reduce or accommodate complexity (Turner, Aitken, and Bozarth 2018), it has not yet addressed the paradoxical situation of *complexity-inducing responses*. In other words, some responses to complexity can inadvertently increase it when implemented. For example, in our findings, responses related to data analytics (Table 3) likely introduce considerable complexity (e.g. many decision models with fluctuating efficacy over time). Their implementation drives additional complexity in finding and acquiring the complementary human skills to use such technologies (e.g. a range of skills with unpredictable market availability). This issue calls for much broader attention within SCC research in general.

Fourth, as our study used a broad interpretation of SCC that encompasses both operations challenges and issues of supply and demand (C. C. Bozarth et al. 2009; Fernández Campos, Trucco, and Huaccho Huatuco 2019; Serdarasan

2013), future research could further explore the specific interactions between internal and external elements in the context of maintenance operations in battery production. For instance, studies could investigate the detailed interconnections between external supply factors and internal operational complexities along with their evolution over time, such as tracing supplier selection risks or the geographical spread of the supplier base to internal uncertainty manifested in equipment novelty. Such research could lead to the development of more nuanced and sophisticated models of SCC that explicitly account for cross-boundary interactions.

Fifth, the extant literature has a predominant focus on the technical aspects of SCC (Ateş et al. 2022; Bode and Wagner 2015; C. C. Bozarth et al. 2009; Serdarasan 2013). This pattern is also reflected in our findings, as most of the identified sources of SCC are technical in nature (e.g. processes, machinery and equipment) and primarily concentrated in the internal manufacturing facility (Table 2). While this is in part explained by the fundamental nature of the maintenance function, i.e. holding the ultimate responsibility for the proper functioning of physical assets in production systems, an important avenue for further research is to focus more specifically on the social and behavioural aspects of complexity in maintenance operations of battery production that our study failed to capture. This has also been called for more broadly in SCC research (Ateş and Luzzini 2023).

5.4. Limitations

The present study has limitations that can be remedied in future research. Substantively, our study is limited in the theoretical domain by focusing on Europe as the geographical setting and with an emphasis on Swedish firms. For example, external factors in the demand and supply environment (Table 2), such as buyer-supplier relations, may manifest differently across cultural and geographical contexts. Our domain was also limited to cell manufacturing and pack assembly plants, and we did not observe or consider battery recycling operations as part of the maintenance scope for a single site. Such facilities will be built at Swedish cell manufacturing sites in the future but were not operational at the time of the study. Moreover, the greenfield pack assembly plants in Sweden are based on more integrated and automated production compared to conventional module and pack assembly.

Methodologically, our exploratory study into battery production as a new phenomenon required a research design that ensured access to key informants and enabled interactions with professionals (Edmondson and McManus 2007; Van de Ven and Johnson 2006). However, it was inherently limited in the number and depth of observations of fully operating battery plants as most Swedish plants are still in the planning, building, or early phases of operations. Furthermore, most identified sources of SCC were related to the internal environment of the manufacturing facility (Table 2). This is, in part, a limitation caused by the positioning of the maintenance function in the internal and lower

organizational hierarchy of manufacturing firms and the consequent difficulty for maintenance professionals to identify and anticipate demand and supply issues that are temporally and geographically distanced from their daily work. Furthermore, we did not consider or analyse the temporal stability of the sources or responses, i.e. if they are expected to be reasonably stable over time. For example, some may be tied to the rapid expansion of the battery production sector and might change or disappear in the future (e.g. scaling issues), while others might be stable and persist (e.g. numerosness of equipment). Also, as our analysis did not seek to separate generic vs. specific features of SCC, further research is needed to tease out sources and responses to SCC that are purely unique to maintenance operations within battery production and which have commonalities with other, similar types of industries (e.g. semiconductor) or substantive contexts (e.g. rapid scaling of greenfield factories). Additional contextual changes to SCC might also arise as new battery technologies (e.g. sodium-ion or (semi-)solid-state) and production techniques (e.g. dry coating) are brought from a lab- and pilot-scale into industrial production.

6. Conclusions

This study addresses the emerging and growing concerns for supply chain complexity in the maintenance of lithium-ion battery production. We examine current and anticipated sources and responses to complexity in cell manufacturing and pack assembly by capturing deep and rich insights from automotive OEMs and battery cell manufacturers within the rapidly emerging battery sector. Specifically, we uncover a wide range of sources of structural and dynamic complexity across the demand, internal and supply environments. We also identify an extensive set of management practices for responding to complexity in maintenance operations. The empirical findings thereby unravel complexity in the maintenance of battery production and provide maintenance practitioners with substantial guidance in designing and implementing strategies for managing complexity. This article thereby sets the agenda for research on the maintenance of battery production and positions supply chain complexity as a versatile theoretical lens for understanding the emerging battery sector, a completely new industrial landscape that plays a central role in the pursuit of electrification and societal decarbonization.

Notes

1. Transport and Environment, https://www.transportenvironment.org/wp-content/uploads/2023/03/2023_03_Battery_risk_How_not_to_lose_it_all_report.pdf.
2. World Economic Forum, http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf.
3. Accenture & Fraunhofer FFB, https://www.ffb.fraunhofer.de/content/dam/ipt/forschungsfertigung-batteriezeile/Dokumente/Whitepaper_The%20Power%20of%20Digitalization%20in%20Battery%20Cell%20Manufacturing.pdf.

4. World Economic Forum, http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf.
5. Fossilfritt Sverige (in Swedish), <https://fossilfritt Sverige.se/wp-content/uploads/2022/03/Finansieringsstrategi-Fossilfritt-Sverige.pdf>.
6. Financial Times, <https://www.ft.com/content/d407772c-4a76-4e59-9bb0-998b3f22383b>.
7. The column 'n' denotes the number of individuals in each category.
8. 'n' refers to the number of times each type of data collection activity was executed.

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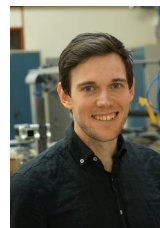
Disclosure statement

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

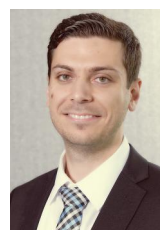
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Notes on contributors



Jon Bokrantz is a Research specialist at the Department of Industrial and Materials Science at Chalmers University of Technology. His research focuses on production and operations management with a special emphasis on industrial maintenance. His research interests include the interplay of technology, people and organization, especially in the context of advancing and diffusing digital technologies to maximize operational performance.



Hafez Shurrab is an Assistant Professor at the College of Business Administration, Ajman University, holding a Ph.D. in Technology Management and Economics from Chalmers University of Technology, Sweden. His academic background includes multiple Master's degrees in industrial engineering and project management, and he also has diverse industrial experience spanning entrepreneurship, volunteering, business development and engineering. His research, resulting in numerous publications, focuses on demand-supply balancing in complex manufacturing operations and digital transformation in supply chains, and his teaching philosophy emphasizes experiential learning.



modelling methodologies, software development, user interfaces and input data architectures.



oper at Volvo Cars.

ORCID

Jon Bokrantz  <http://orcid.org/0000-0003-4930-7786>

Hafez Shurrah  <http://orcid.org/0000-0002-6897-7227>

Björn Johansson  <http://orcid.org/0000-0003-0488-9807>

Anders Skoogh  <http://orcid.org/0000-0001-8519-0736>

Data availability statement

The participants of this study did not give written consent for their data to be shared publicly, so due to the sensitive nature of the research, supporting data is not available.

References

- Abramowski, Johann-Philip, Alexander D. Kies, Enno Hachgenei, Alexander Kreppein, Dennis Grunert, and Robert H. Schmitt. 2023. "Building Blocks for an Automated Quality Assurance Concept in High Throughput Battery Cell Manufacturing." *Procedia CIRP* 120: 904–909. <https://doi.org/10.1016/j.procir.2023.09.097>.
- Afini Normadhi, Nur Baiti, Liyana Shuib, Hairul Nizam Md Nasir, Andrew Bimba, Norisma Idris, and Vimala Balakrishnan. 2019. "Identification of Personal Traits in Adaptive Learning Environment: Systematic Literature Review." *Computers & Education* 130: 168–190. <https://doi.org/10.1016/j.compedu.2018.11.005>.
- Aitken, James, Cecil Bozarth, and Wolfgang Garn. 2016. "To Eliminate or Absorb Supply Chain Complexity: A Conceptual Model and Case Study." *Supply Chain Management: An International Journal* 21 (6): 759–774. <https://doi.org/10.1108/SCM-02-2016-0044>.
- Akkermans, Henk, Rob Basten, Quan Zhu, and Luk Van Wassenhove. 2024. "Transition Paths for Condition-Based Maintenance-Driven Smart Services." *Journal of Operations Management* 70 (4): 548–567. <https://doi.org/10.1002/joom.1295>.
- Anderson, Philip. 1999. "Perspective: Complexity Theory and Organization Science." *Organization Science* 10 (3): 216–232. <https://doi.org/10.1287/orsc.10.3.216>.
- Ateş, Melek Akin, and Davide Luzzini. 2023. "Untying the Gordian Knot: A Systematic Review and Integrative Framework of Supply Network Complexity." *Journal of Business Logistics* 45 (1): 3–30. <https://doi.org/10.1111/jbl.12365>.
- Ateş, Melek Akin, Robert Suurmond, Davide Luzzini, and Daniel Krause. 2022. "Order from Chaos: A Meta-Analysis of Supply Chain Complexity and Firm Performance." *Journal of Supply Chain Management* 58 (1): 3–30. <https://doi.org/10.1111/jscm.12264>.
- Birkie, Seyoum Eshetu, and Paolo Trucco. 2016. "Understanding Dynamism and Complexity Factors in Engineer-to-Order and Their Influence on Lean Implementation Strategy." *Production Planning & Control* 27 (5): 345–359. <https://doi.org/10.1080/09537287.2015.1127446>.
- Bode, Christoph, and Stephan M. Wagner. 2015. "Structural Drivers of Upstream Supply Chain Complexity and the Frequency of Supply Chain Disruptions." *Journal of Operations Management* 36 (1): 215–228. <https://doi.org/10.1016/j.jom.2014.12.004>.
- Bokrantz, Jon, and Jan Dul. 2023. "Building and Testing Necessity Theories in Supply Chain Management." *Journal of Supply Chain Management* 59 (1): 48–65. <https://doi.org/10.1111/jscm.12287>.
- Bokrantz, Jon, Anders Skoogh, Cecilia Berlin, Thorsten Wuest, and Johan Stahre. 2020. "Smart Maintenance: An Empirically Grounded Conceptualization." *International Journal of Production Economics* 223: 107534. <https://doi.org/10.1016/j.ijpe.2019.107534>.
- Bozarth, Cecil, Robert Handfield, and Ajay Das. 1998. "Stages of Global Sourcing Strategy Evolution: An Exploratory Study." *Journal of Operations Management* 16 (2-3): 241–255. [https://doi.org/10.1016/S0272-6963\(97\)00040-5](https://doi.org/10.1016/S0272-6963(97)00040-5).
- Bozarth, Cecil C., Donald P. Warsing, Barbara B. Flynn, and E. James Flynn. 2009. "The Impact of Supply Chain Complexity on Manufacturing Plant Performance." *Journal of Operations Management* 27 (1): 78–93. <https://doi.org/10.1016/j.jom.2008.07.003>.
- Breiter, Andreas, Evan Horetsky, Martin Linder, and Raphael Rettig. 2022. *Power Spike: How Battery Makers Can Respond to Surging Demand from EVs*. New York: McKinsey & Company.
- Brinn, J. 2022. *Electric Vehicle Battery Supply Chains: The Basics*. New York: NRDC.
- Campbell, John L., Charles Quincy, Jordan Osserman, and Ove K. Pedersen. 2013. "Coding in-Depth Semistructured Interviews: Problems of Unitization and Inter-coder Reliability and Agreement." *Sociological Methods & Research* 42 (3): 294–320. <https://doi.org/10.1177/0049124113500475>.
- Cantarelli, Chantal C. 2022. "Innovation in Megaprojects and the Role of Project Complexity." *Production Planning & Control* 33 (9-10): 943–956. <https://doi.org/10.1080/09537287.2020.1837934>.
- Chand, Pushpendu, Anil Kumar, Jitesh Thakkar, and Kunal Kanti Ghosh. 2022. "Direct and Mediation Effect of Supply Chain Complexity Drivers on Supply Chain Performance: An Empirical Evidence of Organizational Complexity Theory." *International Journal of Operations & Production Management* 42 (6): 797–825. <https://doi.org/10.1108/IJOPM-11-2021-0681>.
- Chatha, K. A., and M. N. Jalil. 2022. "Complexity in Three-Echelon Supply Chain Network and Manufacturing Firm's Operational Performance." *Computers & Industrial Engineering* 169: 108196. <https://doi.org/10.1016/j.cie.2022.108196>.
- Corley, Kevin G., and Dennis A. Gioia. 2004. "Identity Ambiguity and Change in the Wake of a Corporate Spin-off." *Administrative Science Quarterly* 49 (2): 173–208. <https://doi.org/10.2307/4131471>.
- Corley, Kevin G., and Dennis A. Gioia. 2011. "Building Theory about Theory Building: What Constitutes a Theoretical Contribution?" *Academy of Management Review* 36 (1): 12–32. <https://doi.org/10.5465/amr.2009.0486>.
- Costantino, Nicola, and Roberta Pellegrino. 2010. "Choosing between Single and Multiple Sourcing Based on Supplier Default Risk: A Real Options Approach." *Journal of Purchasing and Supply Management* 16 (1): 27–40. <https://doi.org/10.1016/j.pursup.2009.08.001>.
- Craighead, Christopher W., Jennifer Blackhurst, M. Johnny Rungtusanatham, and Robert B. Handfield. 2007. "The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities." *Decision Sciences* 38 (1): 131–156. <https://doi.org/10.1111/j.1540-5915.2007.00151.x>.
- Delbufalo, Emanuela. 2022. "Disentangling the Multifaceted Effects of Supply Base Complexity on Supply Chain Agility and Resilience." *International Journal of Physical Distribution & Logistics Management* 52 (8): 700–721. <https://doi.org/10.1108/IJPDLM-07-2021-0302>.

- de Leeuw, Sander, Ruud Grotenhuis, and Ad. R. van Goor. 2013. "Assessing Complexity of Supply Chains: Evidence from Wholesalers." *International Journal of Operations & Production Management* 33 (8): 960–980. <https://doi.org/10.1108/IJOPM-07-2012-0258>.
- Despeisse, Mélanie, Björn Johansson, Jon Bokrantz, Greta Braun, Arpita Chari, Xiaoxia Chen, Qi Fang, et al. 2023. "Battery Production Systems: State of the Art and Future Developments." In *IFIP International Conference on Advances in Production Management Systems*, pp. 521–535. Switzerland: Springer Nature.
- De Stefano, M. Cristina, and Maria J. Montes-Sancho. 2023. "Complex Supply Chain Structures and Multi-Scope GHG Emissions: The Moderation Effect of Reducing Equivocality." *International Journal of Operations & Production Management* 44 (5): 952–986. <https://doi.org/10.1108/IJOPM-11-2022-0759>.
- Dittfeld, Hendryk, Kirstin Scholten, and Dirk Pieter Van Donk. 2018. "Burden or Blessing in Disguise: Interactions in Supply Chain Complexity." *International Journal of Operations & Production Management* 38 (2): 314–332. <https://doi.org/10.1108/IJOPM-03-2017-0158>.
- Duffner, Fabian, Lukas Mauler, Marc Wentker, Jens Leker, and Martin Winter. 2021. "Large-Scale Automotive Battery Cell Manufacturing: Analyzing Strategic and Operational Effects on Manufacturing Costs." *International Journal of Production Economics* 232: 107982. <https://doi.org/10.1016/j.ijpe.2020.107982>.
- Edmondson, Amy C., and Stacy E. McManus. 2007. "Methodological Fit in Management Field Research." *Academy of Management Review* 32 (4): 1246–1264. <https://doi.org/10.5465/amr.2007.26586086>.
- Ennen, Edgar, and Ansgar Richter. 2009. "The Whole Is More than the Sum of Its Parts—Or Is It? A Review of the Empirical Literature on Complementarities in Organizations." *Journal of Management* 36 (1): 207–233. <https://doi.org/10.1177/0149206309350083>.
- Fernández Campos, Pablo, Luisa Huaccho Huatucu, and Paolo Trucco. 2022. "Framing the Interplay Mechanisms between Structural and Dynamic Complexity in Supply Chains." *Production Planning & Control* 35 (6): 599–617. <https://doi.org/10.1080/09537287.2022.2114959>.
- Fernández Campos, Pablo, Paolo Trucco, and Luisa Huaccho Huatucu. 2019. "Managing Structural and Dynamic Complexity in Supply Chains: Insights from Four Case Studies." *Production Planning & Control* 30 (8): 611–623. <https://doi.org/10.1080/09537287.2018.1545952>.
- Fisher, Greg, and Herman Aguinis. 2017. "Using Theory Elaboration to Make Theoretical Advancements." *Organizational Research Methods* 20 (3): 438–464. <https://doi.org/10.1177/1094428116689707>.
- Gerschberger, Markus, Corinna Engelhardt-Nowitzki, Sebastian Kummer, and Franz Staberhofer. 2012. "A Model to Determine Complexity in Supply Networks." *Journal of Manufacturing Technology Management* 23 (8): 1015–1037. <https://doi.org/10.1108/17410381211276853>.
- Gerschberger, Markus, Stanley E. Fawcett, Amydee M. Fawcett, and Melanie Gerschberger. 2023. "Why Supply Chain Complexity Prevails: Mapping the Complexity Capability Development Process." *The International Journal of Logistics Management* 35 (1): 112–135. <https://doi.org/10.1108/IJLM-03-2022-0093>.
- Gligor, David, Ivan Russo, and Michael J. Maloni. 2022. "Understanding Gender Differences in Logistics Innovation: A Complexity Theory Perspective." *International Journal of Production Economics* 246: 108420. <https://doi.org/10.1016/j.ijpe.2022.108420>.
- Gunasekaran, Angappa, Nachiappan Subramanian, and Shams Rahman. 2015. "Supply Chain Resilience: Role of Complexities and Strategies." *International Journal of Production Research* 53 (22): 6809–6819. <https://doi.org/10.1080/00207543.2015.1093667>.
- Guntuka, Laharish, Thomas M. Corsi, and David E. Cantor. 2023. "Recovery from Plant-Level Supply Chain Disruptions: Supply Chain Complexity and Business Continuity Management." *International Journal of Operations & Production Management* 44 (1): 1–31. <https://doi.org/10.1108/IJOPM-09-2022-0611>.
- Hansen, Hans, Sara R. S. T. A. Elias, Anna Stevenson, Anne D. Smith, Benjamin Nathan Alexander, and Marcos Barros. 2023. "Resisting the Objectification of Qualitative Research: The Unsilencing of Context, Researchers, and Noninterview Data." *Organizational Research Methods* 0 (0): 10944281231215119. <https://doi.org/10.1177/10944281231215119>.
- Heim, Gregory R., David Xiaosong Peng, and Shekhar Jayanthi. 2014. "Longitudinal Analysis of Inhibitors of Manufacturer Delivery Performance." *Decision Sciences* 45 (6): 1117–1158. <https://doi.org/10.1111/deci.12102>.
- Huaccho Huatucu, Luisa, Janet Smart, Anisoara Calinescu, and Suja Sivadadan. 2021. "Complexity Transfer in Supplier-Customer Systems." *Production Planning & Control* 32 (9): 747–759. <https://doi.org/10.1080/09537287.2020.1762135>.
- IEA (International Energy Agency). 2022. *Global Supply Chains of EV Batteries*. Paris: IEA.
- Iftikhar, Anas, Laura Purvis, Ilaria Giannoccaro, and Yingli Wang. 2022. "The Impact of Supply Chain Complexities on Supply Chain Resilience: The Mediating Effect of Big Data Analytics." *Production Planning & Control* 34 (16): 1562–1582. <https://doi.org/10.1080/09537287.2022.2032450>.
- Jones, Benjamin, Viet Nguyen-Tien, Robert Elliott, and Gavin Harper. 2022. *Geopolitics and the Supply and Demand of Battery Materials*. London: London School of Economics (LSE) Business Review.
- Kampker, Achim, Peter Burggräf, Christoph Deutschens, Heiner Heimes, and Marc Schmidt. 2012. "Process Alternatives in the Battery Production." Paper presented at the 2012 Electrical Systems for Aircraft, Railway and Ship Propulsion, Bologna, Italy, 16–18 October 2012.
- Ketokivi, Mikko, and Saku Mantere. 2010. "Two Strategies for Inductive Reasoning in Organizational Research." *Academy of Management Review* 35 (2): 315–333.
- Kwade, Arno, Wolfgang Haselrieder, Ruben Leithoff, Armin Modlinger, Franz Dietrich, and Klaus Droeder. 2018. "Current Status and Challenges for Automotive Battery Production Technologies." *Nature Energy* 3 (4): 290–300. <https://doi.org/10.1038/s41560-018-0130-3>.
- Lazim, Halim Mad, Mohamed Najib Salleh, Chandrakantan Subramaniam, and Siti Norezam Othman. 2013. "Total Productive Maintenance and Manufacturing Performance: Does Technical Complexity in the Production Process Matter." *International Journal of Trade, Economics and Finance* 4 (6): 380–383. <https://doi.org/10.7763/IJTEF.2013.V4.321>.
- Lee, S. Shawn, Tae H. Kim, S. Jack Hu, Wayne W. Cai, and Jeffrey A. Abell. 2010. "Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review." Paper presented at the International Manufacturing Science and Engineering Conference, Erie, Pennsylvania, USA, 12–15 October 2010. <https://doi.org/10.1115/MSEC2010-34168>.
- Lincoln, Yvonna S., and Egon G. Guba. 1985. *Naturalistic Inquiry*. Beverly Hills, CA: Sage Publications.
- Liu, Yangtao, Ruihan Zhang, Jun Wang, and Yan Wang. 2021. "Current and Future Lithium-Ion Battery Manufacturing." *iScience* 24 (4): 102332. <https://doi.org/10.1016/j.isci.2021.102332>.
- Lockström, M. 2007. *Low-Cost Country Sourcing: Trends and Implications*. Berlin, Germany: Springer Science & Business Media.
- Maghazei, Omid, Michael A. Lewis, and Torbjørn H. Netland. 2022. "Emerging Technologies and the Use Case: A Multi-Year Study of Drone Adoption." *Journal of Operations Management* 68 (6-7): 560–591. <https://doi.org/10.1002/joom.1196>.
- Mantere, Saku, and Mikko Ketokivi. 2013. "Reasoning in Organization Science." *Academy of Management Review* 38 (1): 70–89. <https://doi.org/10.5465/amr.2011.0188>.
- Marquez, Adolfo Crespo, and Jatinder N. D. Gupta. 2006. "Contemporary Maintenance Management: Process, Framework and Supporting Pillars." *Omega* 34 (3): 313–326. <https://doi.org/10.1016/j.omega.2004.11.003>.
- Matyas, Kurt, Tanja Nemeth, Klaudia Kovacs, and Robert Glawar. 2017. "A Procedural Approach for Realizing Prescriptive Maintenance Planning in Manufacturing Industries." *CIRP Annals* 66 (1): 461–464. <https://doi.org/10.1016/j.cirp.2017.04.007>.
- Maxwell, Joseph A. 2012. *Qualitative Research Design: An Interactive Approach*. Vol. 41. Thousand Oaks, CA: Sage Publications.
- Maylor, Harvey, and Neil Turner. 2017. "Understand, Reduce, Respond: Project Complexity Management Theory and Practice." *International*

- Journal of Operations & Production Management* 37 (8): 1076–1093. <https://doi.org/10.1108/IJOPM-05-2016-0263>.
- Nelson, Paul A., Shabbir Ahmed, Kevin G. Gallagher, and Dennis W. Dees. 2015. "Cost Savings for Manufacturing Lithium Batteries in a Flexible Plant." *Journal of Power Sources* 283: 506–516. <https://doi.org/10.1016/j.jpowsour.2015.02.142>.
- Patton, M. Q. 2014. *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*. Thousand Oaks, CA: Sage Publications.
- Perona, Marco, and Giovanni Miragliotta. 2004. "Complexity Management and Supply Chain Performance Assessment: A Field Study and a Conceptual Framework." *International Journal of Production Economics* 90 (1): 103–115. [https://doi.org/10.1016/S0925-5273\(02\)00482-6](https://doi.org/10.1016/S0925-5273(02)00482-6).
- Ponomarev, Serhiy Y., and Mary C. Holcomb. 2009. "Understanding the Concept of Supply Chain Resilience." *The International Journal of Logistics Management* 20 (1): 124–143. <https://doi.org/10.1108/09574090910954873>.
- Robson, Ian, Udechukwu Ojiako, and Stuart Maguire. 2024. "A Complexity Perspective of Dynamic Capabilities in Enterprise Project Organizations." *Production Planning & Control* 35 (8): 745–769. <https://doi.org/10.1080/09537287.2022.2126953>.
- Salvador, Fabrizio, Aravind Chandrasekaran, and Tashfeen Sohail. 2014. "Product Configuration, Ambidexterity and Firm Performance in the Context of Industrial Equipment Manufacturing." *Journal of Operations Management* 32 (4): 138–153. <https://doi.org/10.1016/j.jom.2014.02.001>.
- Schmich, Richard, Ralf Wagner, Gerhard Hörpel, Tobias Placke, and Martin Winter. 2018. "Performance and Cost of Materials for Lithium-Based Rechargeable Automotive Batteries." *Nature Energy* 3 (4): 267–278. <https://doi.org/10.1038/s41560-018-0107-2>.
- Schnell, Joscha, Corbinian Nentwich, Florian Endres, Anna Kollenda, Fabian Distel, Thomas Knoche, and Gunther Reinhart. 2019. "Data Mining in Lithium-Ion Battery Cell Production." *Journal of Power Sources* 413: 360–366. <https://doi.org/10.1016/j.jpowsour.2018.12.062>.
- Schnell, Joscha, and Gunther Reinhart. 2016. "Quality Management for Battery Production: A Quality Gate Concept." *Procedia CIRP* 57: 568–573. <https://doi.org/10.1016/j.procir.2016.11.098>.
- Schreiber, B., P. Seidel, A. Krug, R. P. Navarro, K. O. Zander, S. Akayama, P. Dutz, and F. Hoffmann. 2022. "Achieving Resilience and Sustainability for the EV Battery Supply Chain." *Prism (Arthur D. Little)*.
- Serdarasan, Seyda. 2013. "A Review of Supply Chain Complexity Drivers." *Computers & Industrial Engineering* 66 (3): 533–540. <https://doi.org/10.1016/j.cie.2012.12.008>.
- Sharma, Amalesh, Surya Pathak, Sourav B. Borah, and Anirban Adhikary. 2020. "Is It Too Complex? The Curious Case of Supply Network Complexity and Focal Firm Innovation." *Journal of Operations Management* 66 (7–8): 839–865. <https://doi.org/10.1002/joom.1067>.
- Shurab, Hafez, and Patrik Jonsson. 2023. "Untangling the Complexity Generating Material Delivery "Schedule Instability": Insights from Automotive OEMs." *International Journal of Operations & Production Management* 43 (2): 235–273. <https://doi.org/10.1108/IJOPM-02-2022-0105>.
- Simon, Herbert A. 1962. "The Architecture of Complexity." *Proceedings of the American Philosophical Society* 106 (6): 467–482.
- Soliman, Marlon, and Tarcisio Abreu Saurin. 2022. "Lean-as-Imagined Differs from Lean-as-Done: The Influence of Complexity." *Production Planning & Control* 33 (11): 1097–1114. <https://doi.org/10.1080/09537287.2020.1843729>.
- Sousa, Rui, and Christopher A. Voss. 2008. "Contingency Research in Operations Management Practices." *Journal of Operations Management* 26 (6): 697–713. <https://doi.org/10.1016/j.jom.2008.06.001>.
- Stark, Andreas, Kenneth Ferm, Robin Hanson, Mats Johansson, Siavash Khajavi, Lars Medbo, Mikael Öhman, and Jan Holmström. 2023. "Hybrid Digital Manufacturing: Capturing the Value of Digitalization." *Journal of Operations Management* 69 (6): 890–910. <https://doi.org/10.1002/joom.1231>.
- Starr, Martin K. 1984. "Global Production and Operations Strategy." *Columbia Journal of World Business* 19 (4): 17–22.
- Suddaby, Roy. 2006. "From the Editors: What Grounded Theory Is Not." *Academy of Management Journal* 49 (4): 633–642. <https://doi.org/10.5465/amj.2006.22083020>.
- Swanson, Laura. 2003. "An Information-Processing Model of Maintenance Management." *International Journal of Production Economics* 83 (1): 45–64. [https://doi.org/10.1016/S0925-5273\(02\)00266-9](https://doi.org/10.1016/S0925-5273(02)00266-9).
- Trent, Robert J., and Robert M. Monczka. 2002. "Pursuing Competitive Advantage through Integrated Global Sourcing." *Academy of Management Perspectives* 16 (2): 66–80. <https://doi.org/10.5465/ame.2002.7173538>.
- Turetskyy, Artem, Sebastian Thiede, Matthias Thomitzek, Nicolas von Drachenfels, Till Pape, and Christoph Herrmann. 2020. "Toward Data-Driven Applications in Lithium-Ion Battery Cell Manufacturing." *Energy Technology* 8 (2): 1900136. <https://doi.org/10.1002/ente.201900136>.
- Turner, Neil, James Aitken, and Cecil Bozarth. 2018. "A Framework for Understanding Managerial Responses to Supply Chain Complexity." *International Journal of Operations & Production Management* 38 (6): 1433–1466. <https://doi.org/10.1108/IJOPM-01-2017-0062>.
- Vachon, S., and R. D. Klassen. 2002. "An Exploratory Investigation of the Effects of Supply Chain Complexity on Delivery Performance." *IEEE Transactions on Engineering Management* 49 (3): 218–230. <https://doi.org/10.1109/TEM.2002.803387>.
- Van de Ven, Andrew H. 2007. *Engaged Scholarship: A Guide for Organizational and Social Research*. Oxford: Oxford University Press.
- Van de Ven, Andrew H., and Paul E. Johnson. 2006. "Knowledge for Theory and Practice." *Academy of Management Review* 31 (4): 802–821. <https://doi.org/10.5465/amr.2006.22527385>.
- Väyrynen, Antti, and Justin Salminen. 2012. "Lithium Ion Battery Production." *The Journal of Chemical Thermodynamics* 46: 80–85. <https://doi.org/10.1016/j.jct.2011.09.005>.
- Vrignat, Pascal, Frédéric Kratz, and Manuel Avila. 2022. "Sustainable Manufacturing, Maintenance Policies, Prognostics and Health Management: A Literature Review." *Reliability Engineering & System Safety* 218: 108140. <https://doi.org/10.1016/j.res.2021.108140>.
- Wessel, Jacob, Alexander Schoo, Arno Kwade, and Christoph Herrmann. 2023. "Traceability in Battery Cell Production." *Energy Technology* 11 (5): 2200911. <https://doi.org/10.1002/ente.202200911>.
- Westermeier, Markus, Gunther Reinhart, and Matthias Steber. 2014. "Complexity Management for the Start-up in Lithium-Ion Cell Production." *Procedia CIRP* 20: 13–19. <https://doi.org/10.1016/j.procir.2014.05.026>.
- Westermeier, M., G. Reinhart, and Tobias Zeilinger. 2013. "Method for Quality Parameter Identification and Classification in Battery Cell Production Quality Planning of Complex Production Chains for Battery Cells." Paper presented at the 2013 3rd International Electric Drives Production Conference (EDPC), Nuremberg, Germany, 29–30 October 2013. <https://doi.org/10.1109/EDPC.2013.6689742>.
- Wiengarten, Frank, Usman Ahmed Muhammad, Annachiara Longoni, Mark Pagell, and Brian Fynes. 2017. "Complexity and the Triple Bottom Line: An Information-Processing Perspective." *International Journal of Operations & Production Management* 37 (9): 1142–1163. <https://doi.org/10.1108/IJOPM-06-2016-0292>.
- Wood, David L., III, Jianlin Li, and Claus Daniel. 2015. "Prospects for Reducing the Processing Cost of Lithium Ion Batteries." *Journal of Power Sources* 275: 234–242. <https://doi.org/10.1016/j.jpowsour.2014.11.019>.
- Zhang, Heng, Chunmei Li, Gebrekidan Gebresilassie Eshetu, Stéphane Laruelle, Sylvie Grugeon, Karim Zaghib, Christian Julien, et al. 2020. "From Solid-Solution Electrodes and the Rocking-Chair Concept to Today's Batteries." *Angewandte Chemie* 132 (2): 542–546. <https://doi.org/10.1002/ange.201913923>.