Sustainability, resilience and innovation in industrial electronics: a case study of internal, supply chain and external complexity

Journal of Economic Interaction and Coordination
https://doi.org/10.1007/s11403-023-00396-7

REGULAR ARTICLE

Sustainability, resilience and innovation in industrial electronics: a case study of internal, supply chain and external complexity

Flavia Cicerelli[1] · **Chiara Ravetti**[1]

Received: 1 February 2023 / Accepted: 18 October 2023

Abstract
The electrical and electronic equipment industry is key to climate and energy transitions, but its activities have a significant environmental footprint. Tangible improvements in the sustainability of this sector are difficult because of the layers of complexity that characterize this industry's products, processes and supply chains. This article analyzes the different facets of complexity relevant to sustainability in the industrial electronics sector, by implementing an in-depth longitudinal case study of a leading Italian business-to-business multinational company. We identify three core dimensions of complexity management that are pivotal for corporate sustainability: *internal complexity*, *supply chain complexity* and *external complexity*. We find that handling sustainability in complex production systems with multitier and multiproduct value chains presents organizational and managerial challenges but also offers new competitive opportunities for resilience and innovation. Once the appropriate metrics, know-how and information flows are established, our results highlight the transferability of sustainable innovations in these complex environments.

Keywords Complexity · Sustainability · Supply chain · Innovation · Electrical and electronic equipment (EEE) · Resilience

JEL Classification L23 · L60 · Q01

Flavia Cicerelli and Chiara Ravetti have contributed equally to this work.

✉ Flavia Cicerelli
flavia.cicerelli@polito.it

Chiara Ravetti
chiara.ravetti@polito.it

[1] Department of Management and Production Engineering (DIGEP), Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Turin, Italy

Published online: 08 November 2023

1 Introduction

Electronics is everywhere in modern Western societies, but so is its environmental impact. Electronic devices and components enable and embed some of the most innovative technologies that are reshaping our world, from robotics to domotics, from electric mobility to artificial intelligence (Rasmussen et al. 2020). The electrical and electronic equipment (EEE) sector is a key enabler of the transitions to renewable energy systems, new modes of circular production and climate-resilient economies (European Commission 2020). However, the growth in the EEE industry comes with a heavy and increasing environmental footprint (De Felice et al. 2014). The production and consumption of EEE face two core problems in terms of environmental sustainability: first, its reliance on scarce minerals and rare metals (Bressanelli et al. 2021), whose extraction causes a wide range of environmental spillovers, and second, the production of a stream of e-waste, as also called WEEE (waste of EEE), containing hazardous substances and potentially valuable materials (Forti et al. 2020; Man et al. 2012).

In this context, the ecological transition to carbon neutrality, circular economy models and systemic improvements in sustainability offer companies in this industry new opportunities for competitiveness, but the process is not without barriers (Rizos and Bryhn 2022). Some companies operating in EEE supply chains are attempting to achieve tangible improvements in the sustainability of their products and processes, but they are facing numerous challenges deriving from the high complexity that reigns over this industry (Menon and Ravi 2021a). One of the most well-studied dimensions of complexity in this sector is in terms of its supply chain. The global scope of electronics supply chains, in fact, exposes companies to the propagation of systemic risks and disruptive events (Jüttner and Maklan 2011; Ponis and Koronis 2012; Tukamuhabwa et al. 2015), which represent both a challenge and an opportunity for complexity management and, ultimately, for improving environmental, social and financial sustainability (Donadoni et al. 2018).

Given the increasing number of international shocks recently affecting the global economy, with the COVID-19 pandemic and ensuing supply chain disruptions as some of the most prominent examples, companies are directing increasing efforts toward developing their resilience strategies, by prioritizing management tools and innovations that support preparedness and long-term stability (Orlando et al. 2022; Pellegrino and Gaudenzi 2023). Consequently, complexity management has the potential to boost resilience and, in turn, competitiveness and sustainability (e.g., Donadoni et al. 2018; Läger et al. 2022; Luo et al. 2017). Moreover, recent studies have provided ample empirical evidence of the growing importance of complexity management in organizations (Pavlov and Micheli 2023; Reeves et al. 2020). For example, among a set of senior executives, a majority perceive the level of complexity within their organizations as excessive and do not have access to appropriate complexity management (Shey and Roesgen 2012). Another study highlights how most managers interviewed believe that, in future, complexity will become an increasingly crucial factor in corporate

administration (Jäger et al. 2014). However, more evidence is required on how complexity management is linked to corporate sustainability management and competitiveness, to better characterize how it can strengthen long-term resilience (Bianchi et al. 2022; Espinosa and Porter 2011; Wiedmer et al. 2021).[1]

Furthermore, the literature has not yet mapped the link between different types of complexity and the implementation of sustainability in concrete business realities, focusing instead on obstacles and enablers of new sustainable approaches (Menon and Ravi 2021b; Zhu and Geng 2013). The specific role that different forms of complexity play in managing corporate sustainability remains largely unexplored, especially in complex sectors with high potential for both positive and negative environmental contributions, such as electronics value chains (Menon and Ravi 2021a). Despite an increasing interest in the nexus between supply chain complexity, supply chain resilience and sustainability (e.g., Birkie et al. 2017; Donadoni et al. 2018; Hussain et al. 2023; Souza et al. 2017; Wiedmer et al. 2021), there is still a substantial gap concerning the impact of managing different dimensions of complexity for corporate sustainability and resilience—not exclusively in the supply chain dimension.

To fill the identified gaps currently existing in the literature, the main goal of this article is to distill the most relevant dimensions of complexity theory for corporate sustainability in a real-life context and use this analysis as a basis for theory building and to identify new opportunities for resilience. In the electronics industry, due to its long history of high complexity of products, processes and supply chains, and increasing geographic dispersion of production, complexity has already been incorporated to a large extent in most companies' strategies. Therefore, in our analysis, the construct of interest is *complexity management,* rather than complexity per se. Moreover, to date, most applied sustainability research of EEE has explored case studies from consumer electronics, thus focusing only on the end of these supply chains (Fang and Rau 2017; Hankammer et al. 2020). Instead, we chose to investigate the impact of different complexity dimensions in the whole supply network, which has been subject to fewer analyses (Akın Ateş et al. 2022), starting from a case study of a first-tier supplier of industrial electronic products and its supply chains.

Overall, our contribution to the existing literature is twofold. First, since the relationship between complexity and corporate sustainability management is not univocal, we want to investigate precisely *how* complexity management is linked to corporate sustainability in this specific setting and thus build a novel framework on the relationship between different types of complexity and Corporate Sustainability Management (CSR). Second, we explore how the identified dimensions of complexity management can impact the adoption of sustainable innovations that increase long-term resilience in the EEE industry. By implementing an in-depth longitudinal

[1] A search of Scopus, Elsevier's largest repository of scientific peer-reviewed publications, for articles containing the keywords "complexity" AND "corporate sustainability" in their title, abstract or keywords yields less than 100 results as of January 2023. Adding the keyword "management" reduces the resulting articles to less than 40.

case study methodology, our research analyzes how complexity is perceived by practitioners, what difficulties it poses, how it is managed and whether it can open new business opportunities, thus enhancing the competitiveness and resilience of an organization.

More precisely, the research questions we want to address are:

- RQ1. How do different dimensions of complexity in the electronic and electrotechnical equipment sector affect corporate approaches to sustainability?
- RQ2. Can the management of complexity and sustainability create innovative sources of resilience and competitive advantage?

Finally, answering these research questions with our case study allows us not only to build a conceptual framework that relates sustainability and complexity management with organizational resilience, but also provides practical managerial implications highlighting how to exploit complexity to incorporate green innovations to handle sustainability as a business opportunity rather than a cost. We find that one key activity that enables the creation of comparative advantage in the joint management of sustainability and complexity is the capacity to effectively transfer innovations, new methodologies and know-how regarding greener solutions across products or clients within a complex system.

The remainder of the paper is organized as follows. Section 2 presents the theoretical background on managing complexity, corporate sustainability and resilience. Section 3 illustrates the methodological approach of the article. Section 4 examines the results of the supporting case study and the emerging conceptual framework. Finally, Sect. 5 concludes with some further discussion, while Appendix shows unstructured questionnaire used for the interviews.

2 Theoretical background

Our research contributes to the literature on complexity management, corporate sustainability strategies and their link with resilience and long-term competitiveness. We examine the most relevant findings for each of these areas of research in the following sections.

2.1 Complexity management and organizations

Complexity is an elusive construct that is often placed at the center of corporate management and strategy, whose interpretation and conceptualization can vary according to the specific research field (Jacobs and Swink 2011). In particular, since the 1960s, complexity has been a dominant concept in the organization research arena (Anderson 1999). A complex system responds to the classic definition of being made of a large number of parts that have multiple interactions (Simon 1962). The level of complexity of the organization tends to grow with increasing abundance (the number of elements that influence each other), correlation (the strength

of mutual relationships) and diversity (Osbert-Pociecha 2013). From this definition, it is possible to classify two different types of complexity. The first one is structural complexity, which refers to the number of different elements constituting the system; the second one is dynamic complexity, which refers to the number of interactions within the system (Bode and Wagner 2015).

In organization theory, complexity has been interpreted as a structural variable characterizing both organizations and their environments and that can have multiple dimensions and categorizations. For instance, vertical complexity captures the number of levels of the organizational hierarchy, horizontal complexity the number of departments across an organization and spatial complexity the number of geographical locations (Daft 1992). Moreover, complexity refers also to the number of different external elements (clients, suppliers, stakeholders) that must be dealt with simultaneously by the organization (Scott 1992). Therefore, an appropriate theoretical framework of complexity management should capture the complexity of an organization's internal structure and technology with the complexity of its external environment (Größler et al. 2006).

The management of the various types of corporate complexity described in the previous paragraphs can be better understood considering the link between different components of complexity and corporate performance, and the relationship between complexity management and overall business management, which can determine the aggregate resilience of an organization. From this perspective, three main dimensions of complexity can be identified at the firm level relevant to our research questions.

The first dimension is *internal complexity*, an extremely broad and nuanced construct that has been differently characterized by previous research (De Toni et al. 2016; Duncan 1972; Glenn and Malott 2004; Vogel and Lasch 2016). According to Glenn and Malott (2004), internal complexity is composed of two main sub-dimensions: *component complexity* and *hierarchical complexity*. The first one refers to the number of elements that constitute an organization and the number of processes each system subsumes, while the second one refers to the number of system levels in the organization, such as the different levels of management. Therefore, a company's internal complexity can rise, for example, when a greater number of employees are hired. Moreover, the more layers of components an organization establishes, the more hierarchical complexity increases. Consequently, hierarchical complexity is typically influenced by component complexity (Glenn and Malott 2004). Vogel and Lasch (2016) propose an extensive literature review aiming at identifying the drivers that contribute to the increase of a company's internal complexity. They differentiate between *internal correlated complexity*, which is influenced by the external market's complexity, and the *internal autonomous complexity*, which, instead, is only determined by internal factors within the company. An exhaustive classification of the main drivers contributing to the internal correlated and autonomous complexity is provided in Table 1.

All these drivers participate in increasing an organization's complexity levels, and they can lead to systems turbulences (Vogel and Lasch 2016). Indeed, rising levels of this complexity dimension have been shown to weaken operational efficiency and decrease profit margins (Hoole 2006). For example, product complexity,

Table 1 Drivers of internal complexity. Source: Authors' elaboration, adapted from Vogel and Lasch (2016)

Internal correlated complexity drivers	Internal autonomous complexity drivers
Target complexity	Organizational complexity
Customer complexity	Process complexity
Product and product portfolio complexity	Production complexity
Technological complexity	Planning, control and information complexity
Product development complexity	Resource complexity
Supply process complexity	Logistics complexity
Service complexity	Sales and distribution complexity
Remanufacturing complexity	

which is one of the drivers, can have several negative implications on supply chain management and processes, related to aspects such as product development, supply of materials and delivery (Closs et al. 2008). Nevertheless, other studies have illustrated that there is a *good complexity* that is essential to create value by increasing revenues, profits and customer loyalty, for example, through product customization (Anderson et al. 2006). Consequently, eliminating complexity is not the solution, while effectively managing internal product complexity can result in greater profits (Meeker et al. 2009), although this management can prove to be a challenging task (Closs et al. 2008).

The second dimension, directly correlated with the first one, is represented by *supply chain complexity*. The literature has highlighted three key sources of supply chain-related complexity: (i) the number of suppliers, (ii) the differentiation among those suppliers and (iii) the relationships among the suppliers (Choi and Krause 2006). Therefore, this dimension is related, but not limited, to "interconnected flows of materials, funds and information between firms" (Bode and Wagner 2015). Supply chain complexity has been identified as a main obstacle to performance efficiency and one of the most demanding issues affecting supply chains (Bozarth et al. 2009). Moreover, this type of complexity has been recognized as one possible cause of supply chain disruptions (Narasimhan and Talluri 2009), which can undermine shareholder value, sales and corporate reputation and weaken relationships with other actors in the chain (Hendricks et al. 2009).

The last dimension is associated with *external complexity,* otherwise known as spatial complexity, which refers to the number of different geographical locations a company must interface with, and their corresponding regulatory and financial implications. The organization must deal continuously with the external locations, directly or indirectly, either because they belong to the organization itself (for instance a production plant located in a foreign country) or to its supply chain (Daft 1992). The literature has emphasized how external complexity fuels supply chain complexity by increasing the risk of supply chain disruption in different ways (Blackhurst et al. 2007; Bode and Wagner 2015). For example, geographically dispersed locations can result in a physically longer flow of inputs, thus increasing transportation times and their variability, requiring more complex logistics systems.

Moreover, the longer the distance between different actors in a supply chain, the greater the information-processing needs and monitoring costs (Bode and Wagner 2015; Stock et al. 2000). The latest evolutions in legal and voluntary requirements regarding corporate social responsibility, especially regarding themes such as decarbonization, climate double materiality and carbon footprints, pose new challenges for companies in terms of the degree of external complexity that firms must handle (Schneider et al. 2017). Recently there has been a new trend in analyzing how companies cope with various forms of external complexity thanks to collaborative strategies (Schneider et al. 2017). Indeed, some companies respond to increasing external complexity by enhancing their internal complexity within their own organization, while others may cooperate with external stakeholders to have access to more information outside of the organization itself.

There are many other classifications and alternative definitions of complexity that describe the dynamic challenges faced by organizations (Barr and Hanaki 2008; Cara et al. 2017; Läger et al. 2022; Liu et al. 2015). However, for our analysis, we choose to focus on these three levels of internal, supply chain and external complexity because they better characterize the areas that can be effectively managed within industrial electronics. Moreover, they allow us to examine some of the core challenges in introducing sustainable practices in this sector, as identified by the literature on transitions to cleaner production (Rizos and Bryhn 2022).

2.2 Corporate sustainability management and complexity

Sustainability is one of the leading issues in the latest business literature since more and more companies are trying to systematically integrate environmental and social evaluations into their processes and decisions (Hahn and Scheermesser 2006). Corporate sustainability is defined as "*the ability to conduct business with a long-term goal of maintaining the well-being of the economy, environment and society*" (Hassini et al. 2012). Therefore, Corporate Sustainability Management (CSM) highlights how the viability of the company is strongly related to the ability to create profit without affecting the socio-ecological environment in which the company operates (Ameer and Othman 2012). Thus, CSM can be interpreted as "*the interdependence between the company, the community and the environmental*" (Rahardjo et al. 2013). Consequently, economic sustainability, the primary objective of every business throughout history, is not a sufficient condition for achieving long-term corporate sustainability (Maia et al. 2022). Moreover, since sustainability needs to be considered and integrated far beyond corporate boundaries, it is necessary to engage stakeholders within an organization and all along the supply chain, both upstream and downstream. For this reason, Sustainable Supply Chain Management (SSCM) is a crucial factor in each sustainability strategy (Rajindra et al. 2019).

There are different levels of integration of sustainability within an organization and its supply chain. Formentini et al. (2016) have identified three main categories: (i) the *sustainability leaders*, namely those adopting a Triple Bottom Line approach (TBL—mainly defined as the expansion of business success metrics to include contributions to environmental health and social welfare, in addition to

the already established economic and financial assessments) by integrating it with Sustainable Supply Chain Management (SSCM); (ii) the *sustainability practitioners*, whose business sustainability approach has a limited focus on one or two dimensions of the TBL, with a SSCM still poorly developed; and, lastly, (iii) the *traditionalists*, whose business approaches are not directly oriented toward sustainable management, but might present some sustainability-related initiatives. Indeed, although the importance of CSM practices can be understood by the company's players, they struggle to implement them, and consequently, they often neglect them (Ameer and Othman 2012).

In this context, understanding how complexity can impact the implementation of CSM is crucial, since it is one of the main challenges to address in terms of organizational management and strategy (Jäger et al. 2014). However, the literature has not yet identified a univocal relationship between managing simultaneously different dimensions of corporate complexity and the adoption of CSM practices, currently allowing for conflicting visions.

On the one hand, the management of corporate sustainability imposes upon companies new layers of complexity that need to be addressed. For example, Schneider et al. (2017) show how the external complexity that a company must handle increases when it needs to integrate corporate sustainability issues. To cope with this increased external complexity, organizations modify "their structures, processes, rules or routines," thereby increasing internal complexity as well (Schneider et al. 2017). Typically, these companies need to introduce several new organizational components, like sustainability teams and departments, internal policies and procedures (e.g., codes of conduct or conflict minerals policies), sustainability reporting, measures aimed at promoting sustainability awareness among employees through training, etc. (Baumann-Pauly et al. 2013; Schneider et al. 2017).

On the other hand, several studies claimed that proper management of corporate complexity can support and facilitate the adoption of sustainability practices (Espinosa and Porter 2011; Läger et al. 2022; Schneider et al. 2017). Espinosa et al. (2011) emphasize how complexity requires companies to "actively cultivate and enrich the conditions for knowledge assimilation" by implementing learning mechanisms and acquiring new skills to adapt to new and unpredictable conditions. These mechanisms are also activated during the adoption processes of CSM practices: to internalize sustainability issues into a company's daily operations, since sustainability is a broad and evolving field, there is a need to approach complex learning processes that enhance new knowledge and skills to embrace this continuous evolution (Bianchi et al. 2022; Kabongo and Boiral 2017).

Overall, our paper complements previous research on barriers and enablers for the implementation of corporate environmental sustainability in the EEE industry (Rizos and Bryhn 2022), by providing evidence of the twofold role that complexity plays within multitier and multiproduct value chains: on the one hand, it presents several challenges for managers approaching sustainability but, on the other hand, if properly managed, it can also offer opportunities for innovation and new areas of competitiveness deriving from sustainable corporate development.

2.3 Resilience, sustainability and complexity management

The concept of resilience has been extensively investigated by different streams of research (Gunderson 2000; Luthar et al. 2000; Rose 2007; Wiedmer et al. 2021; Youn et al. 2011). However, its relevance in the context of corporate management and supply chain management has intensified in the past decade (Chowdhury et al. 2019), especially in relation to corporate sustainability issues (e.g., Ortiz-de-Mandojana and Bansal 2016; Souza et al. 2017; Winnard et al. 2014). This literature has shown how environmental sustainability practices help companies that adopt them to accumulate intangible assets, such as organizational reputation, strategic partnerships and engaged workforce. These companies are also able to better perceive problems in the external environment and adapt accordingly. As a result, these environmental sustainability practices contribute to their resilience and viability in the long term (Ortiz-de-Mandojana and Bansal 2016).

Moreover, global supply chains, such as those in industrial electronics, are increasingly facing a variety of disruptions, caused, for example, by natural disasters, opportunistic behaviors of some actor in the chain or industrial accidents (Macdonald and Corsi 2013), which can dramatically impact the performance of the whole supply chain (Ali et al. 2017; Chowdhury et al. 2019; Jain et al. 2017). In particular, natural disasters and extreme climatic events play a significant role in the rush to strengthen organizational resilience, as the greater scope, occurrence and magnitude of these events are a direct result of the climate crisis we are witnessing (IPCC 2022). The spread of the COVID-19 pandemic is an evident example of the damages that disruptions can provoke to supply chains and more broadly, to global economics (Pellegrino and Gaudenzi 2023; Shen and Sun 2023).

In order to minimize and cope with the potential hazards of these events, organizations are trying to build the required capabilities to ensure the resilience of the system, both at the firm and supply chain level. Accordingly, resilience generally represents the "ability to resist disruptions and recover operational capability after disruptions occur" (Wiedmer et al. 2021), while, in the case of supply chains, it can be considered as "the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost-effective recovery and therefore progress to a post-disruption state of operations" (Tukamuhabwa et al. 2015). As a consequence, management studies have interpreted resilience as the capability of adaptability of the organization (Souza et al. 2017).

As highlighted by Donadoni et al. (2018), complexity is considered one of the main drivers of disruptive events and it can also influence the degree to which businesses can enhance their resilience (Blackhurst et al. 2005; Christopher et al. 2011; Kim et al. 2015). However, the existing literature on the relationship between supply chain complexity and resilience shows inconsistencies when it comes to determining the impact of complexity on managing supply chain disruptions, leading to the emergence of two opposing streams of research. The first one provides evidence that higher levels of complexity can increase the frequency and severity of supply chain disruptions, thus weakening the resilience of the systems involved (Bode and Wagner 2015; Wiedmer et al. 2021). For example, Donadoni et al. (2018) demonstrated how product complexity in a supply network can increase the frequency of

disruptive events, consequently worsening plant performances. On the contrary, the second stream affirms that, by improving and increasing flexibility, a higher level of complexity can strengthen resilience to disruptions (Closs et al. 2008; Craighead et al. 2007; Pettit et al. 2013). Notably, Birkie et al. (2017; 2020) stated that to build resilience and supply chain disruption orientation—the capability of a firm to accumulate and incorporate learning gained from managing the disruptions to improve its future response management system (Hussain et al. 2023)—a certain degree of complexity could be beneficial. Wiedmer et al. (2021) advanced the discourse on this paradox by claiming that supply network complexity can have a double-edged impact on the resilience of supply chains against disruptions, both enhancing recovery after a disruptive event and weakening the resistance to a disruptive event.

Despite the considerable contribution of researchers in analyzing the nexus between supply chain complexity and resilience, there is not an equivalent clear framework for addressing the issue from a more comprehensive perspective of complexity. Indeed, current literature lacks a deeper understanding of the role played by the management of different dimensions of complexity as resilience enablers (Souza et al. 2017).

3 Method

To investigate how complexity in the electronic industry affects the achievement of environmental sustainability, we rely on a qualitative research method, based on an in-depth longitudinal explanatory single case study. This method is appropriate for answering comprehensively "how" and "why" research questions, with "*an empirical inquiry that investigates a contemporary phenomenon within its real-life context*" (Yin 1984). Through this case study, we are able to analyze the details of the sustainability-complexity nexus by adopting a holistic view of the phenomena under scrutiny and their context (Baxter and Jack 2008). With repeated interactions with the pivot company, we have collected numerous sources of detailed data that inform our research question in a real-life scenario (Sibbald et al. 2021). For a novel and relatively unexplored topic, this is an appropriate methodological approach to gather multiple types of information with a high degree of granularity. Moreover, since we want to analyze different dimensions of complexity theory on the implementation of corporate sustainability without a predefined a-priori structure, we adopt a deductive approach, to explore the applicability and relevance of complexity theory in the sustainability contexts (Bitektine 2007; Hyde 2000). Thus, we start from the three main dimensions of complexity defined in the theoretical background and then we analyze the phenomenon in a real-life organizational context by collecting empirical data to understand their role in this specific business setting.

3.1 Description of the case study

This case study focuses on the electrical and electronic equipment (EEE) sector, which encompasses a variety of products, such as semiconductors, sensors, electric

vehicles chargers, switchers, information and communication technologies, as well as sub-sectors, e.g., consumer electronics, white goods, automotive and utilities. In the last decades, the EEE industry has undergone a rapid expansion, becoming the largest and most rapidly growing manufacturing sector in the world (Wath et al. 2010). This is mainly due to the enabler role that these industries have in advancing the digital transformation, mass electrification and circular transition that our society is currently witnessing (European Commission 2020; Rasmussen et al. 2020). The ubiquity of the electronics components makes this industry a compelling case since it allows the analysis of different but interconnected supply chains, all of which face the same sustainability challenges (Zehendner et al. 2021).

Inevitably, this relentless growth in production and consumption is also characterized by a significant increase in environmental impacts and carbon footprint (De Felice et al. 2014), which has aroused the interest of numerous scholars (e.g., Bruno et al. 2021; Favot and Grassetti 2017; Gu et al. 2016; Isernia et al. 2019; Qu et al. 2013) and regulatory bodies. Indeed, the EEE sector plays a vital role in the new policies issued by the European Union, such as the Circular Economy Action Plan, the Sustainable Product Initiative (SPI) and the Circular Electronics Initiative (CEI). On the one hand, the production of electronic devices requires a wide range of raw materials, including metals, minerals and rare earth elements (e.g., gold, silver, platinum, cobalt, palladium, indium and aluminum), thus increasing the pressure on these limited assets (Forti et al. 2020). Moreover, the extraction of these resources is associated with different environmental damages, such as habitat destruction, water pollution and soil contamination (Nelen and Bakas 2021).

On the other hand, the proliferation of EEE components also comes with shortened lifecycles of final products (Qu et al. 2013; Umair et al. 2015), which results in a substantial production of e-waste (WEEE), with rates increasing by 3 to 5% annually, thus ranking as one of the fastest growing waste streams globally (Afroz et al. 2013; Widmer et al. 2005). Consequently, the management of WEEE has emerged as a global concern with far-reaching impacts. Indeed, 54 million metric tons of WEEE were generated globally in 2019. Moreover, this category of waste, due to its important content of critical, valuable and hazardous substances, requires specialized recycling procedures and protocols to prevent environmental and health issues, such as the release of these compounds into the air, bottom ash, dust, soil, water and sediments in surrounding areas, which can, in turn, lead to bioaccumulation and biomagnification (Isernia et al. 2019; Man et al. 2012). However, of the total amount of e-waste generated, only 17% was first appropriately collected and then recycled (Bruno et al. 2021; Forti et al. 2020), thus highlighting the failure of recycling activities in keeping pace with the increasing waste production (Cucchiella et al. 2015; Favot and Grassetti 2017; Isernia et al. 2019).

In addition to the heavy environmental impact, this sector is also characterized by high levels of sustainability complexity, mostly determined by the global structure of its supply chains (Zehendner et al. 2021). The actors operating in these networks are located all around the world, complicating the alignment of sustainability standards through different legislations and increasing the vulnerability to extreme events and propagation of systemic risks. For instance, when severe flooding in 2011 damaged the hard drive production in Thailand, affecting one-quarter of the world's supply,

it took a full year for production to resume to pre-flood levels, disrupting computer manufacturers' supply chains (Haraguchi and Lall 2015; Jüttner and Maklan 2011; Ponis and Koronis 2012; Tukamuhabwa et al. 2015). In light of all these factors, the EEE sector stands as an ideal framework for analyzing the nexus between complexity management, CSM and resilience.

For this reason, this case study relies on a single unit of analysis, represented by the pivot organization, to which we refer as Company Alpha, and, in particular, its electronic division. The company was selected as a case "particularly suitable for illuminating and extending relationships and logic among constructs" (Eisenhardt and Graebner 2007), since the selected organization faces all the complexity dimensions previously identified by the theory. Company Alpha is an Italian manufacturing leader in industrial electronics, with a global presence with sixteen production facilities located in Italy, Poland, Spain, Turkey, China and Mexico, as well as sales offices located in France, Spain, Brazil, Germany, the USA, China, Turkey, Russia and Mexico, and four technical research centers, two of which are located in Italy, one in Germany and the last one in Romania. The complexity of Alpha's operations is embedded in its multinational corporate structure, spanning many legislations, policy regions and cultural boundaries.

Moreover, the company operates as the first tier in different multitier supply chains, and it provides solutions across multiple EEE sectors: energy, automotive, appliances, electronics and HVAC (Heating, Ventilation and Air Conditioning). Within each of these sectors, the company produces multiple products; for example, for its energy clients, it produces smart meters as well as electric car charging stations, two kinds of products embedding different materials, with different production and assembly structures, and, due to their different size, very different carbon footprints. The last aspect that makes this organization a perfect representative case for our analysis is its high level of commitment to pursuing sustainability, mainly represented by efforts and significant investments in training, monitoring and measuring sustainability, and numerous internal and collaborative external projects with other stakeholders to reduce the environmental footprint of the organization.

3.2 Data collection

The data for our in-depth case study relies on the triangulation of multiple sources of evidence (Denzin and Lincoln 1998), adopting a variety of viewpoints from different data sources (Yin 1994). First and foremost, we collect primary data from semi-structured interviews spanning more than a year,[2] with different actors of the company (Table 2). We conducted semi-structured and unstructured interviews with different managers of the company that did not specifically mention complexity (see Appendix for the questionnaire), to obtain detailed and in-depth answers driven by the respondent's personal experience (Lopes et al. 2022). All the interviews were conducted in the presence of at least two researchers: One conducted the interview,

[2] The first systematic contact with the company started in February 2021, but only in September 2021 the collaboration for this research on sustainability strategies was designed.

Table 2 Data collection: an overview of the interviewed Alpha managers and directors

Semi-structured and unstructured interviews			
Interviewee	In Alpha since	Duration	Period
Sustainability manager of the electronic division	2018	1 h	January 2023
Marketing and sales director—energy	2012	1 h	June 2022
Sales and business development manager charging system	2005	1 h	June 2022
Sales director, electronic division North America	2013	1 h	June 2022
Total: 4 interviewees		4 h	

Table 3 Data collection from secondary sources

Description of the data source and year	No. of pages of evidence
Publicly available information	
Sustainability reports from 2017 to 2021	420
Sustainability policy	3
Sustainable values	6
Code of ethics updated in 2021	14
Website	–
Internal documents	
CDP Rating Reports of 2020 and 2021	70
Sustainability questionnaire for Alpha suppliers	3
Carbon Environmental Footprint Certification of the Electronic Division	17
Clients' requests (confidential documents)	27
Total number of pages as sources of evidence	560

while the other(s) took field notes (Yin 2017). All the interviews, which lasted an average of one hour, were recorded and transcribed on the same day to avoid missing details (Kantabutra and Ketprapakorn 2020).

Next, we combine this primary data with all relevant public material published by the firm—Sustainability reports, Codes of Conduct, ESG ratings, Sustainability Policies—and some internal documents, such as presentations for clients, or Carbon Disclosure Project (CDP) ratings (Table 3).

Finally, we gathered further unstructured material from observational notes both from internal meetings, with a "passive presence," namely a non-participant observation approach, in which researchers do not interact with the observed subjects (McKinnon 1988), and from one-to-one and group meetings with different actors of the organization (Table 4). Moreover, we facilitated an internal focus group (Barrett and Twycross 2018) with all the department heads and managers from the electronic division to brainstorm innovative solutions to the challenges posed by sustainability management within their complex setting (Table 5).

Table 4 Data collection from one-to-one meetings with field notes

Participants	In Alpha since	Total duration	Period
Group chemical regulation manager	2009	4.5 h	June 2022
Quality manager of the electronic division	2004	1.5 h	February 2022
Sustainability manager of the electronic division	2018	3 h once a week	From February 2022 to June 2022
Total: 3 participants	–	63.5 h	–

Table 5 Data collection from group meetings and focus group

Participants	Total duration	Period
Weekly meeting with: Sustainability manager Quality manager of the electronic division Process digitalization leader of the electronic division	35 h	February 2022 January 2023
Electronic division management focus group (18 managers)	2,5 h	May 2022
Chemicals management group (8 employees)	2 h	May 2022
Total: 29 participants	39,5 h	–

All data gathered have been organized in a structured written form with the aim of facilitating the analysis and tracking of all passages and not losing important information.

3.3 Data analysis

We perform a content analysis of all the collected data from different sources by following three steps (Comini et al. 2022): First, we undertake a pre-analysis, which mainly refers to the assessment of the collection process and organization of data; second, we carry out an analytic description to define the main codes related to the theoretical categories; and, lastly, we conduct an interferential interpretation to identify contents related to our theoretical definitions of complexity based on the purpose of the research.

To code the semantic materials, we adopt a deductive approach to identify the core elements within the three main complexity categories according to the theoretical model defined in Sect. 2 (Yin 2003); then, we used both line-by-line and paragraph-by-paragraph coding to identify "in vivo codes" (Glaser and Strauss 1967), inherent to second-order themes.

To test the theoretical model and explore our research questions, this study relies on a pattern-matching technique, through which researchers can associate their collected data with the propositions of the theory they wish to test (Campbell 2016), by comparing the "expected pattern," i.e., the theoretical categories or the hypotheses, with the "observed pattern," i.e., the obtained results (Hak and Dul 2009). The starting point of the pattern-matching technique was the formulation of the expected

theoretical pattern (Sinkovics 2018) with the pre-existing theory: We want to verify how the electronic industry, in approaching sustainability, is subject to the three dimensions of complexity, namely internal, supply chain and external, and which one seems predominant. Subsequently, we analyze our data to verify if the identified "in vivo" codes confirm that the EEE industry, in approaching sustainability, struggles with these dimensionalities of complexity and whether some new opportunities emerge.

4 Results

In this section, we present the results from our analysis of all the data collected on our case study, as defined in the previous paragraphs. First, we map the network structure for our company of interest, capturing the three types of complexity defined by the theory. Second, we organize the information resulting from the in vivo coding, and from it, we derive a detailed conceptual framework that is grounded in the theoretical categories but further unpacks the elements within each type of complexity relevant to this context. Lastly, we conceptualize the structure of opportunities for further innovations that a firm operating in the EEE sector could experience in pursuing corporate sustainability and complexity management.

4.1 Mapping the sustainability and complexity network

First, we characterize how the dimensions of complexity apply in the context of our case study. Figure 1 shows graphically how the three dimensions of internal, supply chains and external complexity are interlinked in the real context of the pivot firm of this case study.

A multinational company like the one in our analysis faces complexity on these three different fronts. Starting from the left of Fig. 1, Alpha's suppliers contribute to supply chain complexity, but also to broader external complexity, being located in different countries and jurisdictions. The flow of parts, components and services to the company Alpha from its *n* suppliers[3] encapsulates some sustainability attributes, such as the greenhouse gases that are part of the Scope 3 emissions of the focal company.[4] Moreover, in parallel to the material products' characteristics and carbon footprint, the flows of goods and services may be accompanied by appropriate information tracing the sustainability attributes of those products. These information flows may include official documentation, such as compliance with environmental standards like the REACH regulation on chemicals or the RoHS directive on hazardous substances, but also unofficial data disclosures, for example, a life-cycle assessment of a given product. However, not all suppliers are willing or capable of

[3] Only the electronic division of the company has 1240 different suppliers.

[4] According to the Greenhouse Gas Protocol (GHG Protocol), Scope 3 emissions are all indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions.

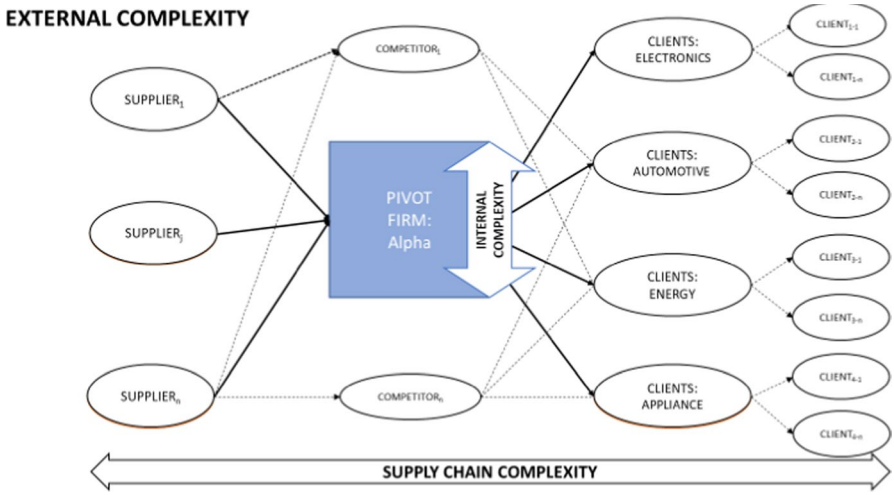

Fig. 1 Network structure of company Alphas' value chains and products, spanning different sectors catered by industrial electronics. The dark continuous arrows capture direct flows of goods and information passing through the pivot company, while the dotted lines capture other exchanges occurring outside of the pivot company. Internal complexity and supply chain complexity are represented by arrows with different lengths according to the areas they span: Internal complexity only refers to the pivot firm, while supply chain complexity refers to all the actors of the chain. External complexity is instead represented by the white space surrounding the pivot firm, the supply chains and all their interrelations. Source: Authors' elaboration, adapted from Bode and Wagner (2015)

providing such information (especially across different countries) or collaborating with their clients to improve the environmental performance of their products. Thus, from the point of view of Alpha, complexity management for sustainability requires a continuous effort in the relationship with its suppliers, both relative to the actual goods and services purchased by the procurement, and relative to data transparency, management and integration along the value chains.[5]

The management of supply chain and external complexity does not only relate to the suppliers, but also to clients operating in different sectors, located in different countries, and each with a different degree of sensibility to environmental priorities (right side of Fig. 1). In the past few years, the company has observed an ever-increasing number of requests related to sustainability from its clients, but the demands are heterogeneous, uncoordinated and often inconsistent. For example, one client requested a minimum reduction in the carbon footprint of a product, but to calculate the reduction initially it allowed for the use of carbon offset certificates, and afterward, a few months it no longer accepted them.

Due to the large number of voluntary standards, global or regional certifications and environmental product declarations and possible metrics available in the

[5] In the long run, the ambition of the focal company is to not only involve direct suppliers, namely 1st suppliers, but also lower tier suppliers, namely producers of raw materials, but to achieve this degree of control over the value chains will require significant support from the direct suppliers.

corporate world to track ESG indicators, B2B companies face a wide range of sustainability requests from their clients. For company Alpha, the demands from clients represent one of the main sources of pressure to identify new and structured systems to handle this growing complexity. One example that emerged frequently from the case study was the management of questionnaires and surveys received from clients regarding sustainability: These uncoordinated data collection activities force the Sustainability Manager to duplicate efforts to convey the same information but always through different platforms or in different formats, without any actual improvements in data management or in the underlying sustainability indicators.

The external and supply chain complexity observed around suppliers and clients directly feeds into the internal complexity of sustainability management within a company (central part of Fig. 1). As company Alpha produces a range of thousands of products,[6] tracking sustainability features for each of them—even just for a few indicators, such as energy consumption or carbon emissions—is a gargantuan task.

The company is investing in training and external experts' support to develop tools to integrate life-cycle assessment (LCA) methodologies in their operations and even to support the design of new products, but the process is difficult because of the lack of ready-to-use interfaces that could be quickly adapted to the company's other data platforms. Information management on sustainability indicators is only the first challenge in handling internal complexity, which then requires building competencies and innovations to improve the sustainability profile of the products and of the different production plants.

4.2 Encoding the elements of complexity affecting sustainability management

The previous section broadly described the different complexity and sustainability challenges faced by company Alpha within its business ecosystem. Next, we apply a textual analysis to all the data collected from the firm over more than one year of in-depth contact and interaction and we structure the results for a more nuanced view of complexity in the context of corporate sustainability. We translate the theoretical categories in an analytical framework grounded in the identified "in vivo codes" (Fig. 2).

The language used by interviewees and official documents does not always directly use the term "complexity," but sometimes refers to an increasing number of requirements, the unpredictability and difficulty in keeping track of many moving elements (sustainability regulations, certifications, clients' priorities, markets' readiness), as well as a wide range of imprecise metrics and measurements, leading to confusing and often deceptive sustainability rankings for different inputs, products or processes.

From this process of categorization of all information provided by company Alpha, we observe an overall alignment between the classic theoretical predictions that complexity increases the strategic difficulty in handling a corporate issue, such

[6] From their product catalogue there are around 2′500 product codes, but the actual product families are fewer, since several products are just small variations of product features.

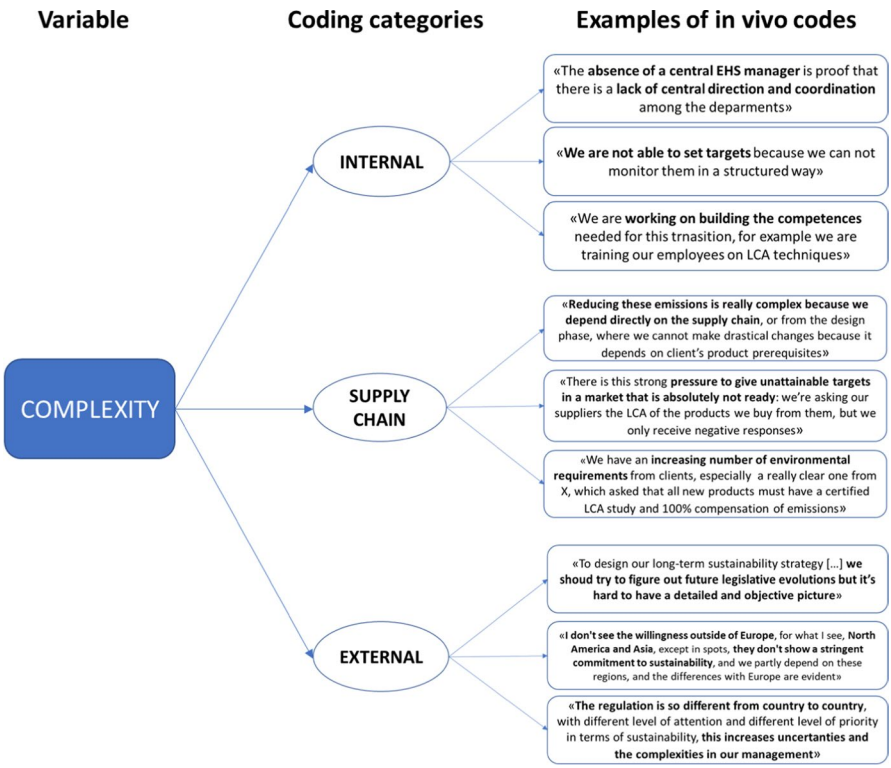

Fig. 2 Analytical framework and data from the case study illustrating each dimension of complexity in sustainability strategies

as sustainability, and the need for innovative approaches to tackle these complexities. Moreover, given the number of occurrences of textual references that can be categorized within the three kinds of complexity, our results demonstrate that the dimensions of internal, supply chain and geographic complexity capture core areas in which complexity affects corporate approaches to sustainability in the EEE sector, here exemplified by the pivot company Alpha. Beyond this general finding, we identify the most frequent topics that emerge from the analysis both within each category of complexity and transversally present in all of them. We use these as a basis to derive a conceptual framework to characterize complexity in the context of sustainability management.

4.3 Conceptual framework emerging from the case study

From the textual analysis described above, we can build a simple conceptual framework that highlights the main elements identified for company Alpha as important issues related to complexity. For each of the three dimensions, following the in vivo coding, we distinguish (i) Some key factors within each dimension, (ii) the

Table 6 Subdivision and specification of the number of elements and interactions constituting each complexity dimension

Complexity dimension	Key factors	Formal and informal linkages between factors	Transversal themes
Internal	Range of competences Multiple products and divisions	Coordination and communications Organization of responsibilities	
Supply chain	Multitier Multisector Multiple stakeholders	Data sharing Contractual obligations	Data measurement, transparency, traceability Innovation in products and processes
External	Competitors Countries and states	Market maturity Regulatory compliance and mandatory disclosures	

formal and informal linkages operating between these factors and (iii) the transversal themes that span all three categories (Table 6). In all cases, the key factors within each area of complexity and the transversal elements emerge from the data as well as consolidated concepts that the company already identifies, while the linking elements are under development, and in many cases refer more to future actions and areas of experimentation.

At the internal level, most issues mentioned (second column of Table 6) refer to the need for more internal expertise, for example on LCA methodologies or the evolution of relevant environmental regulations, and the difficulty in handling the sustainability of different products with different constraints in terms of technologies, quality and safety requirements, size, types of constituent materials and contractual features defined with clients. Their capacity to create sustainability improvements across all the different product categories is limited by the size of their RandD department, which does not specialize in sustainability. The core linkages (third column of Table 6) that the company understands to be necessary to manage both complexity and sustainability in this area are in terms of coordination and communication efforts within the company, and more formally through organizational structures that define and create responsibilities regarding measurements, knowledge-building and innovative decisions.

At the supply chain level, the complexities of greatest concern are the numerous tiers of the value chain, such that the environmental issues of each supplier are also liked to those of their upstream suppliers; the multisectoral nature of the business, with clients from industries with highly differentiated needs in terms of sustainability and different degrees of supply chain integration (for example, the automotive industry already uses advanced data sharing systems to monitor its supply chain, thus making material data declarations the norm, while in utilities, electronics and appliances there are no such systems); and the multiplicity of stakeholders with different requests and priorities. In this case, the links that the company intended to establish over time are first in terms of data sharing arrangements with suppliers

and clients that could be both agile and user-friendly, but also traceable and appropriately confidential. Second, they consider future contractual obligations, so that sustainability requirements could be embedded in formal negotiations and if needed have a reasonable economic valuation.

At the level of external complexity, the sources of pressure derive both from competitors and from legislations and regulations. In this area, the linking elements from company Alpha to these external factors are by definition less under the control of the company but are still to some degree managed as part of an informed sustainability strategy. These include an understanding of market maturity, a highly contextual element that depends on the actions of competitors and other local conditions (such as the sensibility of local final consumers), and a regular monitoring of regulatory trends and in particular requirements for mandatory disclosures on ESG topics around the countries of greatest interest for the group.[7]

Some recurrent themes did not refer to one specific category of complexity but appeared within all of them. The topic of measurement, identifying the right sustainability metrics, data sharing and transparency is perceived in Alpha both as an internal issue—for example, in the context of eco-design approaches to RandD that truly ensure impact reductions—as well as a supply chain issue—especially for the difficulty in accessing sustainability data from suppliers and providing several different forms of ESG disclosures to clients—and lastly also as an external issue, whereby the development of legislations on mandatory disclosures for the future (for example product passports or other forms of compulsory material data declarations) would make this theme particularly urgent. Similarly, the theme of innovations is relevant for all three levels, not only from a technological standpoint but also in terms of innovative solutions. The company is considering radical changes in product design, for instance, eliminating the monitor from metering devices or insulating biomaterials such as wood, but these changes require not only internal coordination to develop the new project, but also cooperation with the supply chain, for example, to convince clients to accept the new products, and finally an understanding of regulatory and market constraints that could hinder or support these innovative products.

4.4 Opportunities for competitive innovations and resilience-building

One central challenge that emerges from the previous analysis is the concern for the lack of a level playing field for fair competition over sustainability attributes. Given

[7] For instance, the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation and the Restriction of Hazardous Substances Directive (RoHS), two of the most relevant EU regulations for the electronics industry, take different forms in Chinese legislation, and in the US do not have an equivalent national counterpart, but only federal laws with different applications. Moreover, the European Union with the adoption of the EU Corporate Sustainability Reporting Directive (CSRD), is gradually requiring European companies to provide increasingly detailed sustainability-related disclosure, clearly advancing beyond other existing global sustainability regulations, which still lack stringency and proactivity. These regulatory inconsistencies, together with all non-written cultural norms and practices across the world, increase the overall external complexity.

the variety of mandatory and voluntary sustainability frameworks, the heterogeneity of desiderata from large clients, and the difficulties in transparently measuring and confronting ESG performance indicators, the challenges of handling multiple levels of complexity in the context of sustainability may seem insurmountable. However, in this current state of confusion and uncertainty regarding corporate sustainability advancement, our results point toward some interesting opportunities for proactive companies willing to become leaders in their sector.

The key managerial opportunity is to transfer sustainability practices, innovations and knowledge across the complex environment in which the company is embedded and use them to build competitive edges and long-term resilience. Despite all of the challenges of this complex system that emerged from the analysis, in our case study several data points indicate a general optimism in the company regarding their ability to respond to complexity in their sustainability strategy: for instance, in their Sustainability Report 2020, they write "*The Group wants to play a leading role and generate value by finding innovative solutions that enable it to understand and respond to the complexity of the context in which it operates.*"

Concretely, the General Manager of the electronic division noted the opportunity to propose to one of their new clients some highly innovative products with a better eco-design, exploiting the previous know-how developed with another product for another client more sensitive to environmental requirements. Similarly, the Quality Manager envisioned an application of digital tools for environmental analyses that were first piloted on one of their smaller products (for the life-cycle assessment of one of their smart meters) and then could provide a basis for the analysis of other larger products (such as EV chargers) that had not yet been measured in terms of their environmental impacts.

To summarize the opportunities for transferability of knowledge and innovations resulting from complexity management as they emerge from the case study, considering the relationship between levels of complexity and sustainability, the following diagrammatic model exemplifies the critical areas. We compare a company that faces a higher degree of internal, supply chain and external complexity, but manages it to its advantage, like company Alpha in our case study, compared to a competitor with a reduced degree of external, supply chain and internal complexity, but also fewer opportunities to identify and exploit new competitive opportunities (Fig. 3).

As seen in our case study, a company operating in a highly complex environment must manage more suppliers, more products and more clients than a competitor company, while straddling numerous markets of operation, both for its own production and in terms of the location of its value chain. However, the diversity of suppliers potentially provides more options to source green inputs and alternative sources of information flows regarding materials (represented by the left arrow in the graph from one supplier to Product 1). A broader suppliers' portfolio can enable the creation of more environmentally friendly products if the company is able to source more sustainable parts and components and produce a more detailed product-level analysis of sustainability.

Moreover, having some innovative green products, eco-designed with clearly measured impacts, allows for a transfer of technologies, metrics, methodologies and design solutions to other products (horizontal thick light blue arrow between

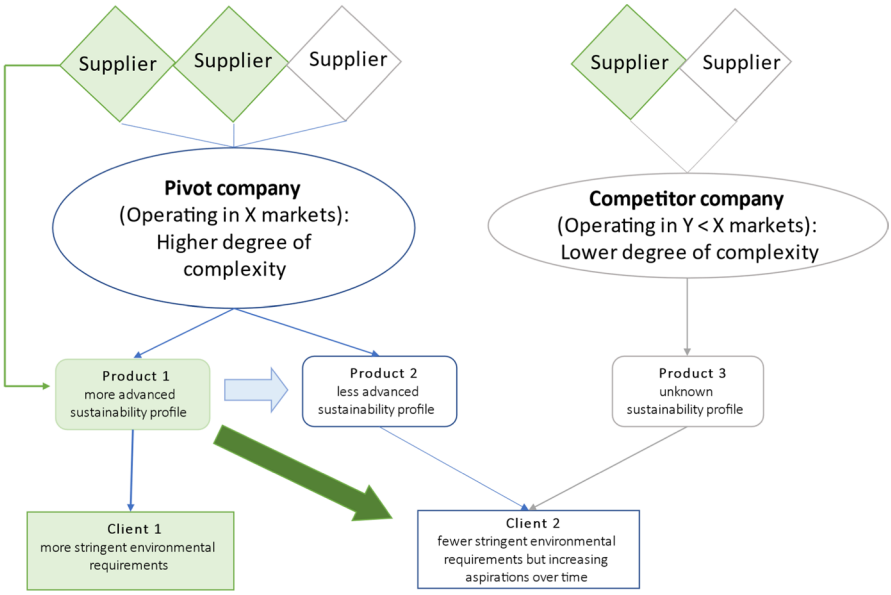

Fig. 3 Sources of competitive advantages from complexity: the pivot company (on the left) has more suppliers, but also more potential sources of information regarding materials' data. Having more products and more clients increases complexity, but also the opportunities to transfer sustainability-related know-how and innovations across products (short thick arrow) and clients (dark thick arrow). The exploitation of internal complexity (multiple products) and external complexity (multiple clients) creates a new competitive advantage through "green sales"

Product 1 and Product 2). Finally, the variety of clients on the one hand increases the complexity of the requests regarding environmental requirements, but also provides an important opportunity to propose to less environmentally sensitive clients some new products, anticipating their future sustainability ambitions. This way, if the client has increasing environmental aspirations for its future, the pivot company can gain preferential access to that client compared to competitors with less experience in these complex ecosystems and therefore less information and fewer innovations. Therefore, the management of complexity can create new sources of competitive advantage if handled strategically across clients, products and supply chains.

Last but not least, the joint management of complexity and sustainability offers innovative solutions for the long-term resilience of the company, as well. This finding is well aligned with the existing literature on complexity management and resilience. For instance, considering supply chain disruptions in the EEE industry, the literature has shown that, following the COVID-19 pandemic, an integrated management approach to information disclosure and cooperation with suppliers and clients has enhanced sustainability, complexity management and resilience (Pellegrino and Gaudenzi 2023; Shen and Sun 2023). According to this literature and as confirmed by our case study, resilience in the context of sustainability and complexity management can also derive from the development of better supply chain relationships, with relational practices that build trust, cooperation, information sharing and mutually

created knowledge that enhance visibility, velocity and flexibility, thus positively impacting performance and competitiveness (Chowdhury and Quaddus 2016; Scholten and Schilder 2015; Wieland and Wallenburg 2013).

These innovative management practices, by enhancing organizational and supply chain resilience, can support companies in the current context of regulatory uncertainty surrounding future legislation on sustainability requirements. Moreover, they allow companies to approach sustainability and complexity management as a risk-management effort to anticipate increasing policy stringency and other future drivers of greater sustainability disclosures and improvements, and thus, to rapidly adapt to continuously changing conditions.

5 Conclusion and future research

In this paper, we investigate how different layers of complexity hinder or favor the implementation of corporate sustainability in the industrial electronics sector. From the theoretical literature, we identify three main dimensions of complexity potentially relevant for sustainability transitions in this industry: internal complexity, supply chain complexity and external complexity. Through an in-depth longitudinal case study of a multinational B2B company serving different markets (utilities, appliances, automotive and electronic), we find that within these categories some key factors are perceived as central challenges to be addressed. Internally, "green" competencies and greener products are the fundamental organizational challenges. For the supply chain, handling multiple tiers, sectors and stakeholders is challenging both for informal information flows and for the design of appropriate contractual obligations relative to sustainability. At the external level, the main issue is keeping track of geographical complexity in rules and laws around the globe, as well as market maturity in different countries driven by competitors' choices.

Two themes emerge from our data analysis that are transversal to all kinds of complexity: data on sustainability indicators and innovations for sustainability improvements. While it remains a core challenge for an EEE company to develop a framework for transparent and efficient data management regarding ESG indicators, both internal and external, and to introduce radical innovations that substantially reduce the carbon footprint and environmental impacts of products and processes, engaging with these challenges can result in new sources of competitive advantage and resilience for the business.

A central source of opportunities for companies in this industry is the transferability of solutions across the complexity-sustainability space. We find evidence that innovative technologies or practices for measurement and improvement of environmental impacts can be transferred between products, and from one client to another. Moreover, the knowledge developed from handling sustainability in legislation and with stakeholders with more advanced sustainability requirements can trickle into other contexts in which the company operates. Managing complexity and sustainability jointly can also support the long-term resilience of a company, mitigating supply chain risks and increasing preparedness for future legislative changes on sustainability.

This study represents a first step in establishing the challenges and opportunities posed by complexity management for corporate sustainability strategies. However, this research is not free of limitations, which may create new opportunities for future research directions. First, the study relies on a single case study which limits the generalizability of our results. Therefore, to test the external validity of the findings, one key extension would be to expand the data analysis to multiple case studies of companies along the entire industrial electronics supply chain, to see how their interlinked strategies affect any improvement in the sustainability of the other companies involved. Company Alpha represents an interesting case study for its position at the intersection of different countries and pressed between large and demanding clients and large input providers located all around the globe. However, the companies serving Alpha or buying its products are equally complex organizations, and thus, an examination of the entire supply chain network could further illuminate this issue.

Second, the analysis focuses on three categories of complexity, namely internal, supply chain and external complexity, which were selected as they characterize the areas that can be more effectively managed within industrial electronics and allow us to examine some of the core challenges in introducing sustainable practices in this sector. However, it could be interesting to investigate if different complexity dimensions capture different challenges. For instance, supply complexity could be more closely related to challenges and opportunities in building a circular economy loop (such as industrial symbiosis solutions), and other companies may represent better examples to study this specific complexity-sustainability nexus. Finally, the resulting conceptual framework has been tailored to the EEE sector, so we recognize that it may not be applicable universally across all sectors and encourage future research to investigate this subject in alternative contexts.

Overall, from this case study, we can conclude that complexity is not exclusively a hindrance to corporate sustainability, but there is evidence that its careful management could also provide opportunities for more sustainable innovations that build competitive advantage and resilience.

Appendix

The unstructured questionnaire used for the interviews was based on the following questions.

1. What responsibilities and projects do you have on sustainability-related issues?
2. What are the priorities? How are they **defined and measured**?
3. With whom does your company **interact internally and externally** to define sustainability targets and requirements?
4. What do you expect from the **supply chain (both from clients and suppliers)**?
5. What are the **formal and informal levers** with which you interact with clients and suppliers on sustainability issues? Do you ever engage tier 2 suppliers (suppliers of suppliers)?

6. Do you have a **uniform sustainability strategy** to deal with all suppliers and clients, or are there **differences** depending on the relationship with individual ones?
7. What **difficulties** do you find in the relationship with suppliers and clients on sustainability?
8. Do you observe any significant **trade-offs** in pursuing your sustainability strategy compared to other strategic areas for your company?
9. What are the most significant **challenges** for your sector in achieving sustainability goals and what **innovations** will be needed, at the supply chain level and beyond?
10. Have you already noticed any **competitive advantages** from the implementation of your sustainability strategy?
11. What plans do you have for the **future** on this issue? What do you imagine will be the main **drivers of further changes**?

Acknowledgements We are grateful to participants of the RandD Management Conference 2022 and AiIG Conference 2022 and to Emilio Paolucci, Luca Ragusa, Giovanni Massari, Alessandra Colombelli, Andrea Tuni and Valeria Dammicco, for useful discussions and comments on this research. All errors remain ours.

Funding Open access funding provided by Politecnico di Torino within the CRUI-CARE Agreement.

Declarations

Conflict of interest The authors acknowledge funding from the Partnership Agreement with Bitron S.p.A. of 13/09/2021 for research, development and innovation in the area "Sustainability." The authors acknowledge financial support from Programma Operativo Nazionale 2014–2020—Dottorati di ricerca su tematiche dell'innovazione e green, according to the D.M. 10 agosto 2021, n. 1061 and D.M. n.1062/2021.

References

Afroz R, Masud MM, Akhtar R, Duasa JB (2013) Survey and analysis of public knowledge, awareness and willingness to pay in Kuala Lumpur, Malaysia—a case study on household WEEE management. J Clean Prod 52:185–193. https://doi.org/10.1016/J.JCLEPRO.2013.02.004

Akın Ateş M, Suurmond R, Luzzini D, Krause D (2022) Order from chaos: a meta-analysis of supply chain complexity and firm performance. J Supply Chain Manag 58(1):3–30. https://doi.org/10.1111/jscm.12264

Ali A, Mahfouz A, Arisha A (2017) Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. Supply Chain Manag Int J 22(1):16–39. https://doi.org/10.1108/SCM-06-2016-0197

Ameer R, Othman R (2012) Sustainability practices and corporate financial performance: a study based on the top global corporations. J Bus Ethics 108(1):61–79. https://doi.org/10.1007/s10551-011-1063-y

Anderson P (1999) Complexity theory and organization science. Organ Sci 10(3):216–232

Anderson B, Hagen C, Reifel J, Stettler E (2006) Complexity: customization's evil twin. Strategy Leadership 34(5):19–27. https://doi.org/10.1108/10878570610684801

Barr J, Hanaki N (2008) Organizations undertaking complex projects in uncertain environments. J Econ Interac Coord 3(2):119–135. https://doi.org/10.1007/S11403-007-0025-Z/METRICS

Barrett D, Twycross A (2018) Data collection in qualitative research. Evid Based Nurs 21(3):63–64. https://doi.org/10.1136/eb-2018-102939

Baumann-Pauly D, Wickert C, Spence LJ, Scherer AG (2013) Organizing corporate social responsibility in small and large firms: size matters. J Bus Ethics 115(4):693–705. https://doi.org/10.1007/s10551-013-1827-7

Baxter P, Jack S (2008) Qualitative case study methodology: study design and implementation for novice researchers. Qualitative Report 13(4):544–559. https://doi.org/10.46743/2160-3715/2008.1573

Bianchi G, Testa F, Boiral O, Iraldo F (2022) Organizational learning for environmental sustainability: internalizing lifecycle management. Organ Environ 35(1):103–129. https://doi.org/10.1177/1086026621998744

Birkie SE, Trucco P (2020) Do not expect others do what you should! Supply chain complexity and mitigation of the ripple effect of disruptions. Int J Logist Manag 31(1):123–144. https://doi.org/10.1108/IJLM-10-2018-0273

Birkie SE, Trucco P, Fernandez Campos P (2017) Effectiveness of resilience capabilities in mitigating disruptions: leveraging on supply chain structural complexity. Supply Chain Manag Int J 22(6):506–521. https://doi.org/10.1108/SCM-01-2017-0009

Bitektine A (2007) Prospective case study design: qualitative method for deductive theory testing. Organ Res Methods 11(1):160–180. https://doi.org/10.1177/1094428106292900

Blackhurst J, Craighead CW, Elkins D, Handfield RB (2005) An empirically derived agenda of critical research issues for managing supply-chain disruptions. Int J Prod Res 43(19):4067–4081. https://doi.org/10.1080/00207540500151549

Blackhurst J, Craighead CW, Elkins D, Handfield RB (2007) International journal of production research an empirically derived agenda of critical research issues for managing supply-chain disruptions. Int J Prod Res 43(19):4067–4081. https://doi.org/10.1080/00207540500151549

Bode C, Wagner SM (2015) Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. J Oper Manag 36:215–228. https://doi.org/10.1016/J.JOM.2014.12.004

Bozarth CC, Warsing DP, Flynn BB, Flynn EJ (2009) The impact of supply chain complexity on manufacturing plant performance. J Oper Manag 27(1):78–93. https://doi.org/10.1016/j.jom.2008.07.003

Bressanelli G, Pigosso DCA, Saccani N, Perona M (2021) Enablers, levers and benefits of circular economy in the electrical and electronic equipment supply chain: a literature review. J Clean Prod 298:126819. https://doi.org/10.1016/J.JCLEPRO.2021.126819

Bruno G, Diglio A, Passaro R, Piccolo C, Quinto I (2021) Measuring spatial access to the recovery networks for WEEE: an in-depth analysis of the Italian case. Int J Prod Econ 240:108210. https://doi.org/10.1016/j.ijpe.2021.108210

Campbell DT (2016) III. "Degrees of Freedom" and the case study. Comp Pol Stud 8(2):178–193. https://doi.org/10.1177/001041407500800204

Cara M, Birkinshaw J, Heywood S (2017) Structural versus experienced complexity: a new perspective on the relationship between organizational complexity and innovation. Adv Strateg Manag 37:115–150. https://doi.org/10.1108/S0742-332220170000037005

Choi TY, Krause DR (2006) The supply base and its complexity: implications for transaction costs, risks, responsiveness, and innovation. J Oper Manag 24(5):637–652. https://doi.org/10.1016/j.jom.2005.07.002

Chowdhury MMH, Quaddus M (2016) Supply chain readiness, response and recovery for resilience. Supply Chain Manag Int J 21(6):709–731. https://doi.org/10.1108/SCM-12-2015-0463

Chowdhury MMH, Quaddus M, Agarwal R (2019) Supply chain resilience for performance: role of relational practices and network complexities. Supply Chain Manag Int J 24(5):659–676. https://doi.org/10.1108/SCM-09-2018-0332

Christopher M, Mena C, Khan O, Yurt O (2011) Approaches to managing global sourcing risk. Supply Chain Manag Int J 16(2):67–81. https://doi.org/10.1108/13598541111115338

Closs DJ, Jacobs MA, Swink M, Webb GS (2008) Toward a theory of competencies for the management of product complexity: six case studies. J Oper Manag 26(5):590–610. https://doi.org/10.1016/j.jom.2007.10.003

Comini GM, Fischer RM, D'Amario EQ (2022) Social business and social innovation: the Brazilian experience. Innov Manag Rev 19(2):140–155. https://doi.org/10.1108/INMR-06-2020-0081/FULL/PDF

Craighead CW, Blackhurst J, Rungtusanatham MJ, Handfield RB (2007) The severity of supply chain disruptions: design characteristics and mitigation capabilities. Decis Sci 38(1):131–156. https://doi.org/10.1111/j.1540-5915.2007.00151.x

Cucchiella F, D'Adamo I, Lenny Koh SC, Rosa P (2015) Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew Sustain Energy Rev 51:263–272. https://doi.org/10.1016/J.RSER.2015.06.010

Daft RL (1992) Organization Theory and Design, 4th edn. West Publishing, USA

De Felice F, Elia V, Gnoni MG, Petrillo A (2014) Comparing environmental product footprint for electronic and electric equipment: a multi-criteria approach. Int J Sustain Eng 7(4):360–373. https://doi.org/10.1080/19397038.2013.865811

De Toni AF, De Zan G, Battistella C (2016) Organisational capabilities for internal complexity: an exploration in the Coop stores. Bus Process Manag J 22(1):196–230. https://doi.org/10.1108/BPMJ-06-2015-0089

Denzin NK, Lincoln YS (1998) Collecting and interpreting qualitative material. Sage, London

Donadoni M, Caniato F, Cagliano R (2018) Linking product complexity, disruption and performance: the moderating role of supply chain resilience. Supply Chain Forum Int J 19(4):300–310. https://doi.org/10.1080/16258312.2018.1551039

Duncan RB (1972) Characteristics of organizational environments and perceived environmental uncertainty. Quarterly 17(3):313–327

Eisenhardt KM, Graebner ME (2007) Theory building from cases: opportunities and challenges. Acad Manag J 50(1):25–32

Espinosa A, Porter T (2011) Sustainability, complexity and learning: insights from complex systems approaches. Learn Organ 18(1):54–72. https://doi.org/10.1108/09696471111096000

European Commission (2020) Changing how we produce and consume: new Circular Economy Action Planshows the way to a climate-neutral, competitive economy of empowered consumers

Fang YT, Rau H (2017) Optimal consumer electronics product take-back time with consideration of consumer value. Sustainability 9(3):385. https://doi.org/10.3390/SU9030385

Favot M, Grassetti L (2017) E-waste collection in Italy: results from an exploratory analysis. Waste Manage 67:222–231. https://doi.org/10.1016/j.wasman.2017.05.026

Formentini M, Taticchi P (2016) Corporate sustainability approaches and governance mechanisms in sustainable supply chain management. J Clean Prod 112:1920–1933. https://doi.org/10.1016/J.JCLEPRO.2014.12.072

Forti V, Cornelis PB, Kuehr R, Garam B, Adrian S, Drisse MB, Cheng Y, Devia L, Deubzer O, Goldizen F, Gorman J, Herat S, Honda S, Iattoni G, Jingwei W, Jinhui L, Khetriwal DS, Linnell J, Magalini F, Zeng X (2020) The global E-waste monitor 2020: quantities, flows, and the circular economy potential

Glaser B, Strauss A (1967) The discovery of grounded theory: strategies for qualitative research. Aldine De Gruyter 17(4):364

Glenn SS, Malott ME (2004) Complexity and selection: implications for organizational change. Behav Social Issues 13(2):89–106. https://doi.org/10.5210/bsi.v13i2.378

Größler A, Grübner A, Milling PM (2006) Organisational adaptation processes to external complexity. Int J Oper Prod Manag 26(3):254–281. https://doi.org/10.1108/01443570610646193

Gu Y, Wu Y, Xu M, Mu X, Zuo T (2016) Waste electrical and electronic equipment (WEEE) recycling for a sustainable resource supply in the electronics industry in China. J Clean Prod 127:331–338. https://doi.org/10.1016/j.jclepro.2016.04.041

Gunderson LH (2000) Ecological resilience—in theory and application. Annu Rev Ecol Syst 31(1):425–439. https://doi.org/10.1146/annurev.ecolsys.31.1.425

Hahn T, Scheermesser M (2006) Approaches to corporate sustainability among German companies. Corp Soc Responsib Environ Manag 13(3):150–165. https://doi.org/10.1002/CSR.100

Hak A, Dul J (2009) Pattern matching. ERIM Report Series Research in Management Erasmus Research Institute of Management.

Hankammer S, Kleer R, Piller FT, Hankammer S (2020) Sustainability nudges in the context of customer co-design for consumer electronics. J Bus Econ 123(91):897–933. https://doi.org/10.1007/s11573-020-01020-x

Haraguchi M, Lall U (2015) Flood risks and impacts: a case study of Thailand's floods in 2011 and research questions for supply chain decision making. Int J Disaster Risk Reduct 14:256–272. https://doi.org/10.1016/j.ijdrr.2014.09.005

Hassini E, Surti C, Searcy C (2012) A literature review and a case study of sustainable supply chains with a focus on metrics. Int J Prod Econ 140(1):69–82. https://doi.org/10.1016/J.IJPE.2012.01.042

Hendricks KB, Singhal VR, Zhang R (2009) The effect of operational slack, diversification, and vertical relatedness on the stock market reaction to supply chain disruptions. J Oper Manag 27(3):233–246. https://doi.org/10.1016/J.JOM.2008.09.001

Hoole R (2006) Drive complexity out of your supply chain. Harvard Bus School Newsletter 3:3–5

Hussain G, Nazir MS, Rashid MA, Sattar MA (2023) From supply chain resilience to supply chain disruption orientation: the moderating role of supply chain complexity. J Enterp Inf Manag 36(1):70–90. https://doi.org/10.1108/JEIM-12-2020-0558

Hyde KF (2000) Recognising deductive processes in qualitative research. J Cetacean Res Manag 3(2):82–90. https://doi.org/10.1108/13522750010322089/FULL/PDF

IPCC. (2022). Climate change 2022: impacts, adaptation, and vulnerability

Isernia R, Passaro R, Quinto I, Thomas A (2019) The reverse supply chain of the e-waste management processes in a circular economy framework: evidence from Italy. Sustainability 11(8):2430. https://doi.org/10.3390/su11082430

Jacobs MA, Swink M (2011) Product portfolio architectural complexity and operational performance: incorporating the roles of learning and fixed assets. J Oper Manag 29(7–8):677–691. https://doi.org/10.1016/J.JOM.2011.03.002

Jäger J, Kluth A, Schatz A, Bauernhansl T (2014) Complexity patterns in the advanced complexity management of value networks. Procedia CIRP 17:645–650. https://doi.org/10.1016/J.PROCIR.2014.01.070

Jain V, Kumar S, Soni U, Chandra C (2017) Supply chain resilience: model development and empirical analysis. Int J Prod Res 55(22):6779–6800. https://doi.org/10.1080/00207543.2017.1349947

Jüttner U, Maklan S (2011) Supply chain resilience in the global financial crisis: an empirical study. Supply Chain Manag Int J 16(4):246–259. https://doi.org/10.1108/13598541111139062

Kabongo JD, Boiral O (2017) Doing more with less: building dynamic capabilities for eco-efficiency. Bus Strateg Environ 26(7):956–971. https://doi.org/10.1002/bse.1958

Kantabutra S, Ketprapakorn N (2020) Toward a theory of corporate sustainability: a theoretical integration and exploration. J Clean Prod 270:122292. https://doi.org/10.1016/J.JCLEPRO.2020.122292

Kim Y, Chen Y-S, Linderman K (2015) Supply network disruption and resilience: a network structural perspective. J Oper Manag 33–34(1):43–59. https://doi.org/10.1016/j.jom.2014.10.006

Läger F, Bouzzine YD, Lueg R (2022) The relationship between firm complexity and corporate social responsibility: international evidence from 2010–2019. Corp Soc Responsib Environ Manag 29(3):549–560. https://doi.org/10.1002/csr.2219

Liu H, Ma L, Huang P (2015) When organizational complexity helps corporation improve its performance. J Manag Develop 34(3):340–351. https://doi.org/10.1108/JMD-05-2013-0071/FULL/PDF

Lopes JM, Gomes S, Pacheco R, Monteiro E, Santos C (2022) Drivers of sustainable innovation strategies for increased competition among companies. Sustainability 14(9):5471. https://doi.org/10.3390/SU14095471

Luo XR, Wang D, Zhang J (2017) Whose call to answer: Institutional complexity and firms' csr reporting. Acad Manag J 60(1):321–344. https://doi.org/10.5465/amj.2014.0847

Luthar SS, Cicchetti D, Becker B (2000) The construct of resilience: a critical evaluation and guidelines for future work. Child Dev 71(3):543–562. https://doi.org/10.1111/1467-8624.00164

Macdonald JR, Corsi TM (2013) Supply chain disruption management: severe events, recovery, and performance. J Bus Logist 34(4):270–288. https://doi.org/10.1111/jbl.12026

Maia RG, Junior AO, Pessanha JF, Garcia KC (2022) Methodology for setting corporate sustainability targets. J Clean Prod 369:133359. https://doi.org/10.1016/J.JCLEPRO.2022.133359

Man M, Naidu R, Wong MH, Wong M (2012) Persistent toxic substances released from uncontrolled e-waste recycling and actions for the future. Sci Total Environ 463:1133–1137. https://doi.org/10.1016/j.scitotenv.2012.07.017

McKinnon J (1988) Reliability and validity in field research: some strategies and tactics. Account Audit Account J 1(1):34–54. https://doi.org/10.1108/EUM0000000004619/FULL/PDF

Meeker B, Parikh D, Jhaveri M (2009) The complexity conundrum. Market Manag 18(1):54–59
Menon RR, Ravi V (2021a) An analysis of barriers affecting implementation of sustainable supply chain management in electronics industry: a Grey-DEMATEL approach. J Modell Manag 17(4):1319–1350. https://doi.org/10.1108/JM2-02-2021-0042/FULL/PDF
Menon RR, Ravi V (2021b) Analysis of barriers of sustainable supply chain management in electronics industry: an interpretive structural modelling approach. Clean Responsib Consum 3:100026. https://doi.org/10.1016/J.CLRC.2021.100026
Narasimhan R, Talluri S (2009) Perspectives on risk management in supply chains. J Oper Manag 27(2):114–118. https://doi.org/10.1016/j.jom.2009.02.001
Nelen D, Bakas I (2021) Improving the climate impact of raw material sourcing. Eur Environ Agency (EEA). https://doi.org/10.2800/722698
Orlando B, Tortora D, Pezzi A, Bitbol-Saba N (2022) The disruption of the international supply chain: firm resilience and knowledge preparedness to tackle the COVID-19 outbreak. J Int Manag 28(1):100876. https://doi.org/10.1016/J.INTMAN.2021.100876
Ortiz-de-Mandojana N, Bansal P (2016) The long-term benefits of organizational resilience through sustainable business practices. Strateg Manag J 37(8):1615–1631. https://doi.org/10.1002/smj.2410
Osbert-Pociecha G (2013) Increasing complexity as a challenge for contemporary organizations. Management 17(1):7–18
Pavlov A, Micheli P (2023) Rethinking organizational performance management: a complexity theory perspective. Int J Oper Prod Manag 43(6):899–915. https://doi.org/10.1108/IJOPM-08-2022-0478
Pellegrino R, Gaudenzi B (2023) Impacts and supply chain resilience strategies to cope with COVID-19 pandemic: a literature review. Supply Chain Resil 2023:5–18. https://doi.org/10.1007/978-3-031-16489-7_1
Pettit TJ, Croxton KL, Fiksel J (2013) Ensuring supply chain resilience: development and implementation of an assessment tool. J Bus Logist 34(1):46–76. https://doi.org/10.1111/jbl.12009
Ponis ST, Koronis E (2012) Supply chain resilience: definition of concept and its formative elements. J Appl Bus Res (JABR) 28(5):921. https://doi.org/10.19030/jabr.v28i5.7234
Qu Y, Zhu Q, Sarkis J, Geng Y, Zhong Y (2013) A review of developing an e-wastes collection system in Dalian, China. J Clean Prod 52:176–184. https://doi.org/10.1016/j.jclepro.2013.02.013
Rahardjo H, Idrus MS, Hadiwidjojo D, Aisjah S (2013) Factors that determines the success of corporate sustainability management. J Manag Res 5(2):1–16. https://doi.org/10.5296/JMR.V5I2.2993
Rajindra R, Burhanuddin B, RukhayatiWekke RIS (2019) Sustainable supply chain governance mechanisms: strategic approaches to corporate sustainability. Int J Supply Chain Manag 8(2):232–240
Rasmussen M, Izsak K, Shauchuk P (2020) Advanced technologies for industry: sectoral watch: technological trends in the electronics industry. https://doi.org/10.2826/272688
Reeves M, Levin S, Fink T, Levina A (2020) Taming Complexity. Make sure the benefits of any addition to an organization's systems outweigh its costs. Harv Bus Rev 2020:1–11
Rizos V, Bryhn J (2022) Implementation of circular economy approaches in the electrical and electronic equipment (EEE) sector: barriers, enablers and policy insights. J Clean Prod 338:130617. https://doi.org/10.1016/J.JCLEPRO.2022.130617
Rose A (2007) Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions. Environ Hazards 7(4):383–398. https://doi.org/10.1016/j.envhaz.2007.10.001
Schneider A, Wickert C, Marti E (2017) Reducing complexity by creating complexity: a systems theory perspective on how organizations respond to their environments. J Manage Stud 54(2):182–208. https://doi.org/10.1111/JOMS.12206
Scholten K, Schilder S (2015) The role of collaboration in supply chain resilience. Supply Chain Manag: an Int J 20(4):471–484. https://doi.org/10.1108/SCM-11-2014-0386
Scott WR (1992) Organizations: rational natural and open systems. Prentice-Hall Ed, Hoboken
Shen ZM, Sun Y (2023) Strengthening supply chain resilience during COVID-19: a case study of JD.com. J Oper Manag 69(3):359–383. https://doi.org/10.1002/joom.1161
Shey V, Roesgen R (2012) Mastering complexity. Focus Topic Paper
Sibbald SL, Paciocco S, Fournie M, van Asseldonk R, Scurr T (2021) Continuing to enhance the quality of case study methodology in health services research. Healthc Manage Forum 34(5):291–296. https://doi.org/10.1177/08404704211028857
Simon HA (1962) The architecture of complexity. Proc Am Philos Soc 106(6):467–482
Sinkovics N (2018) Pattern matching in qualitative analysis. SAGE Handbook Qual Bus Manag Res Methods: Methods Chall 2018:468–484. https://doi.org/10.4135/9781526430236.N28

Souza AAA, Alves MFR, Macini N, Cezarino LO, Liboni LB (2017) Resilience for sustainability as an eco-capability. Int J Climate Change Strateg Manag 9(5):581–599. https://doi.org/10.1108/IJCCSM-09-2016-0144

Stock GN, Greis NP, Kasarda JD (2000) Enterprise logistics and supply chain structure: the role of fit. J Oper Manag 18(5):531–547. https://doi.org/10.1016/S0272-6963(00)00035-8

Tukamuhabwa BR, Stevenson M, Busby J, Zorzini M (2015) Supply chain resilience: definition, review and theoretical foundations for further study. Int J Prod Res 53(18):5592–5623. https://doi.org/10.1080/00207543.2015.1037934

Umair S, Björklund A, Petersen EE (2015) Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. Resour Conserv Recycl 95:46–57. https://doi.org/10.1016/J.RESCONREC.2014.11.008

Vogel W, Lasch R (2016) Complexity drivers in manufacturing companies: a literature review. Logist Res 9(1):25. https://doi.org/10.1007/s12159-016-0152-9

Wath SB, Vaidya AN, Dutt PS, Chakrabarti T (2010) A roadmap for development of sustainable E-waste management system in India. Sci Total Environ 409(1):19–32. https://doi.org/10.1016/J.SCITOTENV.2010.09.030

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M, Böni H (2005) Global perspectives on e-waste. Environ Impact Assess Rev 25(5):436–458. https://doi.org/10.1016/J.EIAR.2005.04.001

Wiedmer R, Rogers ZS, Polyviou M, Mena C, Chae S (2021) The dark and bright sides of complexity: a dual perspective on supply network resilience. J Bus Logist 42(3):336–359. https://doi.org/10.1111/jbl.12264

Wieland A, Wallenburg CM (2013) The influence of relational competencies on supply chain resilience: a relational view. Int J Phys Distrib Logist Manag 43(4):300–320. https://doi.org/10.1108/IJPDLM-08-2012-0243

Winnard J, Adcroft A, Lee J, Skipp D (2014) Surviving or flourishing? Integrating business resilience and sustainability. J Strateg Manag 7(3):303–315. https://doi.org/10.1108/JSMA-11-2012-0059

Yin RK (1984) Case study research: design and methods. Sage, Newbury Park

Yin RK (1994) Case study research: design and methods, 2nd edn. Sage Publications, London

Yin RK (2003) Case study research: design and methods. Sage, London

Yin RK (2017) Case study research and applications: design and methods, 6th edn. Sage, London

Youn BD, Hu C, Wang P (2011) Resilience-driven system design of complex engineered systems. J Mech Des 133(10):101011. https://doi.org/10.1115/1.4004981

Zehendner AG, Sauer PC, Schöpflin P, Kähkönen A-K, Seuring S (2021) Paradoxical tensions in sustainable supply chain management: insights from the electronics multi-tier supply chain context. Int J Oper Prod Manag 41(6):882–907. https://doi.org/10.1108/IJOPM-10-2020-0709

Zhu Q, Geng Y (2013) Drivers and barriers of extended supply chain practices for energy saving and emission reduction among Chinese manufacturers. J Clean Prod 40:6–12. https://doi.org/10.1016/J.JCLEPRO.2010.09.017