Sizing the roles: An exploratory research about Logistics 4.0 diffusion

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Abstract

Logistics 4.0 (L40), derived from Industry 4.0, received increasing interest over the recent years. Despite such growing attention, there are few empirical studies examining its actual implementation by firms. This paper offers empirical evidence on L40 diffusion, focusing on small- and medium-sized enterprises (SMEs) versus large enterprises (LEs). Based on interviews with 65 Italian firms, supplemented by secondary data and on-site visits, the study explores L40 adoption from various perspectives: technologies, application areas, drivers, performance improvement, and solution maturity. The findings reveal successful implementation of L40, resulting in tangible benefits; however, the maturity of the technologies/solutions implemented remains low. The study highlights how firms shape their digital transformation accordingly to their size. This study is one of the first empirical contribution to advance the debate on L40 diffusion rate, providing a comprehensive overview of the L40 transition in Italy and size-dependent transformation trajectories towards the digitalization of logistics processes.

Keywords

Logistics 4.0, Innovation Diffusion, Firm Size, Interview Study

Article classification

Research paper

1 Introduction

Logistics 4.0 (L40) is a concept derived from Industry 4.0 (I40) with a high level of interest from both academic and managerial perspectives (Monferdini et al., 2024; Olsen and Tomlin, 2019). Regarded as a complementary approach to I40, L40 consists of introducing cyber-physical systems (CPS) into logistics processes for an improvement in performance through automation, process and actors integration, and intelligent, real-time data-driven decision-making (Oztemel and Gursev, 2020; Loske and Klumpp, 2021; Modica et al., 2021; Wong, Soh and Goh, 2015). The expected benefits are manifold, such as increased speed, efficiency, and cost advantages, while also enabling new services and business models (Choi et al., 2022). As a result, research interest in this area has constantly increased during the last five years (Chung, 2021; Montecchi, Plangger and West, 2021), with many efforts focused on

demonstrating L40 strategic role in shaping the new business landscape (Tang and Veelenturf, 2019) and addressing challenges related to the integration of digital technologies in logistics processes (Li and Li, 2022). Typical L40 applications include: data-driven decision-making and operations in warehouses; real-time tracking and tracing systems; big data and data analytics; AI tools for predicting delays in distribution processes and optimising delivery routes; predictive maintenance enabled by data analytics and machine learning; and blockchain technology, which facilitates process automation, reduces paperwork, and enhances traceability. These applications illustrate how L40 technologies can transform logistics by fostering greater connectivity and synchronization of material flows, automation, and agility. For instance, companies such as DHL and Amazon have leveraged L40 technologies to optimize their supply chain operations, while Maersk has successfully implemented blockchain technology to streamline documentation and improve transparency in its logistics network. Shippers like IKEA and Decathlon have similarly adopted automation in stores and RFId technologies, respectively, to ensure more efficient and responsive global distribution networks. Another example of L40 transformation in real-life companies is provided by Castellucci et al. (2024), considering the inbound logistics process.

Despite these promising applications, it seems that the diffusion of L40 technologies remains expensive, risky, and difficult to achieve (Winkelhaus and Grosse, 2020). Notwithstanding the growing number of publications on the topic, few empirical studies exist about what firms are doing and whether they are really implementing these new technologies (Mathauer and Hofmann, 2019). Most research relies on literature reviews or theoretical analyses, which are insufficient for exploring the complexities of this rapidly evolving field (Wang and Sarkis, 2021). Yet, Given the continuous technological developments in the field, it is critical to expand the methodological approaches used to study L40, particularly those that offer empirical insights into how these technologies are being implemented in practice.

The need for additional research is also true for papers aimed at offering useful insights from professionals in L40 transition processes, which mainly rely on expert interviews (e.g. Hofmann and Rüsch, 2017; Pourmehdi et al., 2021). So far, studies on 4.0 diffusion have mainly focused on I40 (Tortorella and Fettermann, 2018; Masood and Sonntag, 2020; Ardolino et al., 2022), and findings indicate that the overall implementation rate has been low. Nevertheless, evidence exists about an increased diffusion rate over the past few years (Ardolino et al., 2022; Castellani, Lamperti and Lavoratori, 2022), accelerated by the Covid-19 pandemic (Wang and Sarkis, 2021). As further empirical research is necessary to fully understand the L40 phenomenon (Wang and Sarkis, 2021; Hazen, Overstreet and Cegielski,

2012), we argue that analyzing data from a representative sample could be beneficial to better outline the phenomenon in detail and to support the study of firms' attitudes and behaviors towards L40 adoption with empirical evidence. Indeed, logistics is a key component of firms' digital transformation, and transitioning to the L40 paradigm is essential for realizing the full potential of I40 (Hofmann and Rüsch, 2017).

The pace and extent of L40 diffusion vary significantly depending on firm-specific factors, including size. According to some authors, large enterprises (LEs) are more likely to adopt and integrate L40 technologies, while SMEs often face challenges in accessing the necessary financial and technological resources (Marchet, Perego, and Perotti, 2009; Kinkel, Baumgartner, and Cherubini, 2022). At the same time, some studies suggest that size alone does not determine the success of L40 adoption, as SMEs may achieve significant advancements in digital transformation under the right conditions (Lin et al., 2018; Orji et al., 2020).

Based on this discussion, we argue that there is a need to advance the study of L40 diffusion by understanding the current diffusion rate in firms and investigating the factors that influence it, particularly in relation to firm size. Indeed, little evidence exists about the diffusion rate of L40 practices and the maturity of the L40 solutions implemented (e.g. Cichosz, Wallenburg and Knemeyer, 2020). Understanding the current diffusion rate of L40 and how factors like firm size affect its adoption is critical since the diffusion of L40 is necessary not only for firms to remain competitive but also to meet industry standards, where digital technologies are becoming indispensable (Sindhwani et al., 2022). Furthermore, the constrained availability of resources exacerbates the challenges of adopting new logistics technologies (Khanzode et al., 2021). Therefore, analyses and role model concepts are in clear need as a multitude of small and medium-sized firms as well as lager firms in logistics are struggling with the challenges provided by L40 adoption and the digital transition in the sector. Moreover, the lack of clarity regarding the role of firm size in determining the outcome of L40 diffusion provides an opportunity to explore this open debate on innovation diffusion. Therefore, this paper aims to answer the following research questions:

RQ.1 How are L40 technologies diffused among firms in logistics?

RQ.2 How does firm size influence the diffusion of Logistics 4.0?

The study answers these questions by investigating the current state of diffusion of L40 solutions through an interview study involving a sample of 65 firms. Moreover, the study

explores how firms are adopting L40 according to their size, to offer further insights on how to drive the transition toward the fourth industrial paradigm. Italy was chosen as the empirical context of the study as a representative market for L40 implementation. Focusing on a single country could improve results interpretation, since each country is characterized by a different logistics landscape, leading to different adoption levels and motivations for adoption. We believe that Italy is an interesting research target, as it is the second-largest manufacturing country in Europe (Ardolino et al., 2022), and one of the European countries with the highest traffic volumes (Ministero delle Infrastrutture e dei Trasporti, 2020). Therefore, it could experience significant benefits from I40 adoption. Moreover, there is evidence of I40 initiatives implementation and willingness to adopt through government policy (Ministero dello Sviluppo Economico, 2016). Therefore, we believe that this favorable environment towards I40 could reflect an interest in L40 practices as well.

Our findings indicate that L40 diffusion is an ongoing process in the Italian logistics sector, and support the theoretical argument that firm size plays a role in shaping firms' digital transformation strategies. This research contributes to the broader debate on L40 diffusion by providing empirical evidence on the diffusion of L40 solutions and on the relationship between firm size and supply chains' digital transformation. Additionally, the study offers managerial implications since firms' resources are often scarce, and their L40 technologies implementation must be well-informed by studies like ours. Last, policy implications can be derived from the research that supports the development of funding policies for the 4.0 transition.

The paper is structured as follows: Section 2 presents a literature review on the definition of L40 and the role of firm size in determining its diffusion. Section 3 offers an overview of the research methodology. Section 4 presents the findings. We discuss the main results in section 5 and present our conclusions in section 6, offering an outlook for theoretical contribution, managerial implications, and further research.

2 Literature review

2.1. Logistics 4.0 definition

L40 emerged as the application of the core concepts of the fourth industrial revolution – CPS – to logistics operations to enhance automation and decision-making (Hofmann and Rüsch, 2017; Matana et al., 2020). CPS integrate physical and digital systems via information networks, providing the foundation for intelligent industrial automation and business

intelligence (Choi et al., 2022). Thanks to the digitalization of the system's physical elements, CPS enable machine-to-machine and human-to-machine communication and cooperation in real-time, facilitating decentralized, data-driven decisions (Lasi et al., 2014). To this effect, similarly to I40, L40 facilitates real-time monitoring and synchronization of the real world logistics processes with the virtual space through the physical-virtual connection and the networking of CPS elements (Negri et al., 2017). This is supported by a range of technologies, including the Digital Twin, which creates digital replicas of physical assets and processes. The Digital Twin can simulate these elements, exploiting a real-time synchronization of the sensed data coming from the field (Negri et al., 2017).

Being a field of recent inquiry, knowledge about L40 has grown in an unstructured way over the years, and no commonly shared definition currently exists (Winkelhaus and Grosse, 2020). Researchers are still working to understand and define various aspects of L40. One example is the concept of the Supply Chain Digital Twin (SCDT), which represents the application of the Digital Twin to supply chains. The SCDT creates digital replicas of supply chain processes for monitoring, controlling, and simulation. While L40 and SCDT are closely related, they have distinct contributions to the field of logistics and supply chain management fields. Their distinction is quite recent as the interest around SCDT and its definition strongly emerged after the Covid-19 pandemic (Ivanov, 2023; Cimino et al., 2024). Several authors have reviewed the existing literature in an attempt to unify diverse approaches in L40 research and provide elements for its conceptualization (Garay-Rondero et al., 2019; Winkelhaus and Grosse, 2020). Others have focused on structuring the body of knowledge around specific L40-related topics or technologies. For example, Chung (2021) discussed the challenges of integrating smart technologies into optimization methodologies, while Nguyen et al. (2018) organize knowledge related to big data-driven operations and supply chain management from 2000 onwards. Despite ongoing debates regarding a single, universally accepted definition of L40, scholars agree on three core principles that highlight the value brought by digital transformation: "Automation", "Integration" and "Intelligence" (Modica et al., 2021). Automation involves the introduction of autonomous systems able to perform tasks without human intervention (e.g., automated guided vehicles, drones, mobile robots (Hofmann and Rüsch, 2017), as well as the automatic, real-time acquisition of data from physical systems through technologies such as Radio-Frequency Identification (RFID) or the Internet of Things (IoT) (Culot et al., 2020; Seyedghorban et al., 2020). Integration refers to L40's ability to connect and communicate, facilitating process integration and data exchange among the supply chain actors (Ghadge et al., 2020). Finally, Intelligence encompasses business intelligence and data-driven decision-

making, which are expected to 'strike at the very heart of what humans preserve, namely, knowledge work' (Choi et al., 2022), bringing dramatic improvements into current logistics practices.

2.2. Logistics 4.0 diffusion and firm size

Rogers, Singhal and Quinlan, (2019) define innovation as "an idea, practice or object that is perceived as new by an individual or other unit of adoption" (pg. 11). Since "the comprehensive nature of its definition requires firms to individually define what Logistics 4.0 means to them" (Hofmann and Rüsch, 2017), and given the lack of extensive evidence on L40 diffusion, we argue that L40 can be regarded as a technological innovation. It is new to many logistics firms and it is closely linked to the introduction of technological innovation. Being L40 an umbrella term that encompasses various technologies, each at a different stage of maturity in delivering on the value proposition – including, but not limited to, operational efficiency, improved service level, and enhanced decision-making quality – its diffusion follows a continuous evolutionary process, moving from low to high levels of L40 maturity (Cichosz, Wallenburg and Knemeyer, 2020). The diffusion of innovation is a complex and critical management topic that has been widely investigated by scholars (Rogers 1995; Hazen, Hanna and Hall, 2013). Various overlapping terms, such as adoption or integration, have been used to describe the diffusion of innovation (Hazen, Overstreet and Cegielski, 2012), with authors refining and extending its definition, to incorporate multiple stages into the diffusion process (Zhu and Kraemer, 2005). In this paper, we focus on diffusion at its final stage, concentrating on firms that have successfully integraed new technologies or solutions into their processes and are currently using them extensively (Mathauer and Hofmann, 2019). To incorporate the evolutionary perspective of digital transformation, we link the concept of diffusion with the one of maturity, classifying each technology or solution according to its degree of transformation of logistics processes (Modica et al., 2021).

While many scholars have explored the diffusion of I40 in manufacturing across various contexts and countries, including Italy (Ardolino et al., 2022), the Czech Republic (Basl, 2017), Brazil (Tortorella and Fettermann, 2018), India and the U.S. (Wamba and Queiroz, 2020), the UK (Masood and Sonntag, 2020) and China (Lin et al., 2018), L40 diffusion has received far less attention. Although L40 and I40 are closely related, both relying on digital technologies to improve processes and decision-making, they differ in significant ways. L40 extends beyond factory borders to encompass logistics processes, such as distribution, throughout the entire supply chain, requiring multi-actor coordination and integration (Hofmann and Rüsch, 2017), with a consequent increase in the adoption complexity compared

to I40 (Cichosz, Wallenburg and Knemeyer, 2020). Authors discussing L40 diffusion in logistics and supply chain mainly have primarily focused on specific steps of the diffusion process, investigating the main technological, organizational, and environmental factors affecting firms' decisions to adopt digital technologies (Patterson, Grimm and Corsi, 2003; Asare, Brashear-Alejandro and Kang, 2016). Scholars have also highlighted the challenges of integrating L40 technologies into firms' processes (Pourmehdi et al., 2021; Sindhwani et al., 2022) as well as the relationship between specific decisions (e.g., the technology access mode) and successful integration of digital technologies (Mathauer and Hofmann, 2019; Hazen, Overstreet and Cegielski, 2012). While some authors have conceptualized how the Covid-19 pandemic changed the way supply chains approached the digital transformation, shifting from limited pre-pandemic adoption to the deployment of effective digital business strategies during post-pandemic recovery (Sundarakani et al., 2024), few studies provide a comprehensive overview of L40 diffusion rates, with little evidence regarding the maturity and the advancement of the L40 solutions implemented (e.g. Cichosz, Wallenburg and Knemeyer, 2020).

There is evidence in the literature that the diffusion of L40 is influenced by various factors, classified as Technological, Organizational, and Environmental ones (i.e., TOE framework) (Asare, Brashear-Alejandro and Kang, 2016). Among these, firm size remains one of the most debated. Many authors identify a significant positive correlation between the size of a firm and its ability to adopt and exploit new technologies (Marchet, Perego and Perotti, 2009; Kinkel, Baumgartner and Cherubini, 2022). Large firms, with substantial financial resources, are often better positioned to invest in L40 technologies successfully integrate them into their processes (Zhu and Kraemer, 2005; Szász et al., 2020; Hopkins, 2021; Wong, Soh and Goh, 2015; Machado et al. 2024). This was also observed among SMEs: larger firms were more likely to adopt 4.0 technologies and derive greater benefits (Masood and Sonntag, 2020). Despite this evidence, other authors argue that no significant correlation exists between the firm size and L4.0 adoption (e.g. Lin et al., 2018; Orji et al., 2020). These findings are coherent with the broader debate on the role of firm size as a predictor for a firm's ability to innovate, with authors arguing that it is not firm size per se that affects the innovation diffusion, but this relationship needs to be refined to understand what is the real driver of innovation diffusion (Ahuja, Lampert and Tandon, 2008; Lee and Kim, 2014; Dhir et al., 2023). In this regard, authors started investigating why firms of different sizes have different outcomes of the innovation diffusion process. Large firms tend to have greater financial resources and absorptive capacity (ACAP), which are considered good predictors for the successful

implementation of new technology (Schilling, 2013; Mathauer and Hofmann, 2019). However, large firms also tend to become highly formalized, developing bureaucratic structures that hinder innovation diffusion process (Kamien and Schwartz, 1982; Lee and Kim, 2014). Conversely, SMEs are often more flexible and responsive to technological changes (Lee and Kim, 2014) but may face barriers such as resistance to change, and limited human and financial resources (Evangelista and Sweeney, 2006; Sindhwani et al., 2022). These limitations may prompt SMEs to form partnerships and alliances to pursue technology innovation (Mathauer and Hofmann, 2019).

Given the lack of clear empirical insights on L40 diffusion, there is a strong need to investigate firms' attitudes towards L40 practices and solutions. Such insights are crucial for extending the L40 implementation knowledge on a general not further. This could help firms and governments target their effort toward embracing the fourth industrial revolution and realize its associated benefits.

3 Methodology

To examine L40 diffusion and assess the impact of firm size on this process, a semi-structured interview study involving 65 Italian firms was conducted. In this study, "L40" is defined as any solution, tool, or system that provides one or more of the following functionalities to logistics processes by leveraging digital technologies: intelligent automation of physical tasks, real-time data gathering and analysis, physical-digital systems coupling, collaboration between systems and actors, intelligent decision-making (Modica et al., 2021). The next sections describe the sample (section 3.1), and the execution of the study and the analysis conducted (section 3.2).

3.1. Sample

To investigate the impact of firm size on L40 diffusion, we involved SMEs and LEs, considering both logistics service providers (LSPs) and shippers (i.e. manufacturing firms and retailers) from a wide range of industry sectors. Interviewees were selected through purposive sampling, a method that involves recruiting individuals based on specific characteristics or experiences that make them suitable informants (Lundgren et al., 2022). This approach ensured that all respondents had sufficient oversight and decision-making authority regarding the design and management of the logistics processes within their firms. Consistently, firms were selected from a list of contacts provided by the Contract Logistics Observatory "Gino

Marchet" supported by Politecnico di Milano; the Observatory has collaborated with Logistics Managers, Logistics Directors and Supply chain Managers from Italian firms since 2018 to develop and share knowledge about L40. Therefore, the companies involved are assumed to have a high level of understanding of L40 concepts. SMEs and LEs were classified according to the number of employees, with SMEs defined as firms with fewer than 250 employees (Sindhwani et al., 2022). To ensure the study's relevance, we targeted managers with at least five years of work experience in the areas of logistics, supply chain, or innovation management. A total of 475 firms were contacted via e-mail, and personal phone calls were made to improve the response rate, which reached 14%, resulting in 65 firms agreeing to participate in the interviews. Table I summarizes the key characteristics of the sample.

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Table I - Sample characteristics

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3.2. Execution

The interviews were conducted in Italian between February 2022 and June 2022. The questions broadly focused on the firm and interviewee's background, the main L40 projects, solutions and technologies developed by the firm, including their development stage, implementation path and the ways in which these innovations transformed logistics and supply chain processes. Additionally, the interviews investigated the performance improvements firms sought through L40 solutions, as well as the drivers that facilitated the successful integration of these solutions in the logistics and supply chain processes. Given the exploratory nature of the study, the interviews remained open-ended to allow participants to freely express their opinions and experiences regarding specific issues. The interview questions underwent pre-testing through several methods. First, three researchers with over 10 years of experience in logistics and innovation reviewed the questions for relevance and clarity. Subsequently, two pilot interviews were conducted – one with the Logistics Director of a SME and the other with the Supply Chain Manager of a LE. The interviewees received semi-structured questionnaires in advance and the interviews lasted approximately two hours. To ensure the reliability of the findings, secondary data were collected from the firms' websites, reports, publicly available information, and on-site visits. This provided additional background and context for the interview data, enabling data triangulation.

3.3. Analysis

To ensure our coding process aligned with the existing literature, we employed a mixed coding approach, combining both deductive approach by defining codes a priori based on extant literature, and inductive approach, where codes emerge from interview data as significant themes (Campbell et al., 2013). First, according to the deductive approach, we identified relevant themes from the literature (i.e., I order concepts and II order themes) such as L40 technologies and solutions, drivers of L40 diffusion, L40 performance improvements, and L40 maturity levels. These pre-defined themes were used by two researchers to independently code the data collected. Since our objective was to uncover differences in L40 diffusion in LEs and SMEs, data from the two groups were coded separately. As coding progressed, researchers also employed an inductive approach, and identified new themes that emerged directly from the interview data. In a second phase, they frequently interacted to discuss the generated codes, aiming to achieve inter-coder reliability and resolve discrepancies. This collaborative process further refined the coding themes into aggregate dimensions. Finally, a third researcher reviewed all resulting codes to enhance the robustness of the analysis.

Table II summarizes and describes the codes adopted for the analysis, including the references considered for the a priori coding activity. These codes cover various aspects, including the technologies supporting L40 solutions, the logistics processes impacted by L40 transformations, the drivers facilitating L40 diffusion, the performance improved by the introduction of L40 and the maturity of the L40 solution implemented. Building on the framework from Modica et al. (2021), maturity was assessed through two perspectives: horizontal and vertical. The horizontal maturity perspective evaluates the maturity level of the technology adopted in terms of the value if offers, categorised into four levels: (1) Visibility & monitoring, technologies that provide real-time reporting of process or environmental data; (2) Planning & control, technologies that control and organize processes or resources based on pre-defined logics, (3) Predictability & Optimization, technologies that use algorithms to forecast events and optimize operations or resources, enhancing decision-making, and (4) Self-organization & Adaptability, solutions that autonomously react and adapt to external and internal input to improve performance. The vertical maturity perspective assessed the combination of different technologies, that together transform logistics processes according to the three L40 principles mentioned above, “Automation”, “Integration” and “Intelligence”. These principles offer additional value to the overall logistics process (Modica et al., 2021): (i)

Automation concerns performing processes or activities (e.g. movement, data acquisition) with minimal human intervention; (ii) Integration entails sharing collected information across different processes or actors in the supply chain; (iii) Intelligence provides decision-makers with relevant data analysis to support decentralized decision-making at various levels. The vertical maturity of a logistics process is determined by the number of L40 principles adopted, with firms that incorporate all three principles representing the highest maturity level. Both horizontal and vertical maturity perspectives are closely related to the specific technology adopted by the firm, and the capabilities that the technology provides for the process (Fettermann et al., 2018). This two-dimensional maturity model allows us to capture both the technological depth and the systemic integration of L40 practices in the firms under study. For example, firms at the highest maturity levels combine real-time data acquisition (Automation), integration across supply chain partners (Integration), and data-driven decision-making (Intelligence), providing enhanced flexibility and responsiveness across logistics processes (Modica et al., 2021).

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Table II - Codes definition

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4 Results

This section outlines the main findings that emerged from the interview study. First, we present the main evidence about L40 diffusion in Italy, focusing on similarities among firms (section 4.1). Next, we discuss the differences in L40 diffusion between SMEs and LEs (section 4.2).

4.1. Logistics 4.0 diffusion in Italy: technologies, target areas, and diffusion drivers

The discussion about L40 diffusion is organized according to the main themes that emerged from the interviews. First, an overview of the main L40 technologies adopted by firms is provided. This is followed by a discussion on the target areas, highlighting the logistics processes most affected by the transition. Finally, we provide an overview of the main drivers behind L40 diffusion.

L40 is a technology-driven paradigm incorporating various and diverse technological applications (Patrucco, Ciccullo and Pero, 2020). The interview study identified seven categories of technologies connected to the L40 paradigm, and implemented by firms: (a) Advanced automation technologies including robots, cobots, and exoskeleton supporting

warehousing activities, (b) Autonomous vehicles including automated guided vehicles (AGV), laser-guided vehicles (LGV) and drones, (c) Internet of things and sensors, (d) Mobile-based systems including mobile applications supporting logistics activities, (e) Vertical and horizontal integration technologies, including software such as the warehouse management system and transportation management system, (f) Digital platforms for supply chain actors integration, and (g) Advanced analytics, including big data analysis techniques such as artificial intelligence (AI), and digital twin. Advanced automation technologies (32% of the sample, corresponding to 21 firms) are the most adopted among firms in our sample; vertical and horizontal integration technologies and mobile-based systems follow (28% corresponding to 18 firms, and 22% corresponding to 14 firms respectively). Concerning the main areas targeted by the L40 diffusion, Warehouse management including the management of inventory, storage, and material handling operations is the one with the higher diffusion rate of L40 solutions (60% corresponding to 39 firms), followed by transportation management (31% corresponding to 20 firms). Human resources management also emerged as a transversal target area for L40 initiatives:

> One of our most successful L40 projects is the development of a planning system based on AI that supports us in planning the shifts of both warehouse operators and drivers (Innovation manager, LSP, Food industry, LE).

> We implemented a software package that manages and plans the tasks of warehouse workers according to actual resource utilization and information about the forecasted inbound and outbound flows (Supply chain manager, Shipper, House durables, LE).

Concerning L40 diffusion drivers, most firms (52% corresponding to 34 firms) consider L40 a strategic objective, driven by their broader digitalization strategy. Having a strategy that supports the digitalization of the entire firm enables coherent implementation of separate 4.0 technologies and solutions across all business processes. Some firms have created specific roles, such as "Business Process Manager" (Logistics manager, LSP, Food, LE), to oversee the digitalization process and support the re-engineering of processes to integrate L40 solutions.

> The digitalization strategy is our map: in pursuing our transition toward Logistics 4.0 we sometimes use bottom-up approaches, where a technology or a solution is developed by a single department. The main problem of the bottom-up approach is the compatibility and integration between the different technologies at the overall firm level. It is, therefore, necessary to complement it with a top-down strategic approach to ensure that all technologies work together and are aligned with the firm’s objective (CEO, LSP, Industrial and Machinery, LE).

In addition to strategy, ease of technology implementation was cited as a key driver of L40 diffusion (52% corresponding to 34 firms). The user experience resulted extremely relevant for L40 diffusion: the interface between the operators and the technology must be simple and convenient to use, easing the routinization of the change in the process workflow implied by the digitalization.

> It is essential that the technology is easy to use, otherwise, the operators' initial resistance won't be overcome, and the adoption will fail (Logistics Manager, Shipper, Food, SME)

Government incentives are reported as the second most reported diffusion driver (29% corresponding to 19 firms). National programs such as the "Piano Nazionale Industria 4.0" (Ministero dello Sviluppo Economico, 2016), provide fiscal and tax benefits to encourage the adoption of 4.0 technologies. These incentives were primarily used by LEs (35% corresponding to 12 firms) to reduce the cost of investing in advanced automation technologies. Only 23% of SMEs (7 firms) reported these incentives as a relevant driver in the diffusion of L40 solutions. Instead, the SMEs transition is driven by supply chain actors: 35% of the SMEs (11 firms) reported that they introduced L40 solutions under specific requests from other supply chain partners. In general, 28% of the sample (18 firms) perceived supply chain actors' requirements as a driver for L40 diffusion. The same relevance was attributed to the need for enhancing data availability and quality. Firms see L40 as a way to enhance the reliability of the information used for decision-making, ultimately improving the quality of decisions. Additionally, firms recognized that competitiveness is a factor that drives L40 investments. 22% of firms (14 firms) reported that competitors' adoption of L40 solutions prompted them to align with the market trends. Finally, a small percentage of firms (5% corresponding to 3 firms), all SMEs, reported that the need to replace outdated machinery or software was one of the main drivers that pushed them to update their current instruments implementing L40 solutions.

4.2. The role of firm size in Logistics 4.0 diffusion

The results of the interview study reinforce the idea that L40 maturity for the logistics process is a complex concept that includes two perspectives: one related to the maturity level of the technology adopted, in terms of value offered (i.e. horizontal maturity), the other referred to the combination of different technologies, that together contribute to change logistics processes according to the three L40 principles, thus offering additional sources of value to the overall process (i.e. vertical maturity). The research revealed that L40 is diffused among both LEs and SMEs, but most of the firms are in the early development stage with no firm reaching

the highest maturity stage for both maturity perspectives. In terms of horizontal maturity, evidence suggests that firms are primarily focused on the following stages: Visibility & Monitoring (66%, or 43 firms), Planning & Control (18%, or 12 firms), and Predictability & Optimization (12%, or 9 firms). For what concerns vertical maturity, most firms (75% corresponding to 49 firms) have incorporated only one principle in their L40 adoption, while 25% (16 firms) have adopted two principles. No firm has yet implemented all three principles simultaneously. The research also highlighted differences in how LEs and SMEs approach L40 adoption. These differences are related to the maturity level that the logistics process achieved in both maturity perspectives, the type of technological solutions adopted, and the performance improvement sought when adopting L40. Tables III-VI summarize the results.

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Table III - Research results on L40 horizontal maturity by firm size

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Table IV- Research results on L40 vertical maturity by firm size

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Table V - Research results on L40 technologies by firm size

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Table VI - Research results on performance improvement by firm size

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Firm size and Logistics 4.0 maturity

The interview study shows that LEs are, on average, more advanced than SMEs in terms of horizontal maturity, with 26% (9 firms) and 12% (4 firms) reaching stage 2 – Planning & control – and stage 3 – Predictability & optimization – respectively. Nevertheless, the research reveals that a higher percentage of SMEs (19% corresponding to 5 firms) also achieved stage 3 – Predictability & Optimization. For what concerns vertical maturity, the diffusion of L40 solutions for LEs is mainly focused on the Automation principle (44% corresponding to 15

firms). This focus aligns with the direction of the technological investments made by this group of firms, including Advanced automation, Autonomous vehicles, and IoT, which underwent by 83% of LEs. In this regard, robots and autonomous vehicles such as AGV and LGV supporting different warehouse activities including storage, picking, sorting and packing represent the most frequent investments. IoT sensors and RFID are also applied, on Unit Loads for track and trace purposes mainly. Drones and exoskeletons are more niche investments, with two firms using drones to speed up and to increase the accuracy of inventory, and one firm that invested in exoskeletons to assist warehouse workers in their operations. Firms with a higher vertical maturity level combine the Automation principle with the Integration principle (18% of the sample corresponding to 6 firms), sharing real-time information gained from IoT technologies with other supply chain actors to improve decision-making in adjacent logistics processes.

> We first introduced RFID tags for the outbound flows of our factory warehouse to automate control activities and reduce errors. After one year, we developed a digital platform to share this RFID information with our logistics service provider. These data, enriched with further information regarding the shipment and the truck's estimated time of arrival, enabled our logistics service provider to improve the planning of receiving activities (Logistics Manager, Shipper, Food, LE)

On the contrary, the majority of SMEs (42%, corresponding to 13 firms) focus on Integration as their primary vertical maturity principle. Their main investment effort target technologies such as Vertical and horizontal integration systems, Mobile-based systems and Digital platforms. In this respect, firms applied L40 technologies to support real-time and seamless communication with business partners, relying for example on logistics apps for sharing digital proofs of delivery, and on web-based platforms for exchanging information and documents in an electronic format. SMEs also show greater committment to the Intelligence principles than LEs, supported by advanced analytics solutions such as Big data analytics techniques, mainly in an attempt to structure their performance monitoring and to improve their decision-making.

> "We're trying to structure our performance monitoring and make better use of our massive amount of unstructured data." (Logistics manager, Shipper, House durables, SME).

Among firms with two principles implemented, there is a balance between the two possible configurations that include the Integration principle (i.e., Integration + Automation, and Integration + Intelligence). SMEs pairing Integration with Automation focus on collecting data

in an automated way and sharing it with partners, while those pairing Integration with Intelligence aim to use shared data to improve their internal logistics processes.

> We started by sharing automatic and real-time stock data with our retailers to improve the reordering process. So far, a lot of work has been done and data analysis and reporting tools have been put in place to monitor our proper stock sizing based on shortages and out-of-stock. Now the time would be ripe to also work on the opposite front, that of overstock. Our data processing system, in addition to highlighting long cover situations, is also able to determine the causes of these situations, which may be due either to overestimated sales forecasts or to overproduced quantities for other reasons (Supply Chain Manager, Producer, Food, SME)

In fact, SMEs that start to share data with partners often realise the opportunity that this data offers to create efficiencies in their processes. So, once they have data, they use it by feeding data analysis and optimization algorithms.

Firm size and Logistics 4.0 performance improvement

During the interview study, we asked firms about the performance improvements they sought when adopting L40. The results reveal that LEs and SMEs differ not only in terms of maturity and technology but also in the types of performance improvements they prioritize.

Efficiency remains the main performance improvement sought when adopting L40. Both LEs and SMEs pointed out that the implementation of L40 solutions was aimed at reducing costs and increasing the productivity of their resources and processes. Results show that most of LEs consider efficiency as their main priority when investing in L40, followed by improvements in time and quality . SMEs priorities seem more diverse, with more than half of the sample citing quality as their main target alongside efficiency. Among SMEs that reported quality as their main target, the need for reducing errors during logistics activities such as picking or inbound and outbound controls represents the main quality improvement sought. Improving data quality is also a key theme, with managers emphasizing the importance of ensuring traceability:

> "The need to have instruments ensuring the availability and the quality of traceability data is of utmost importance for our business since we have no formal procedure for collecting and structuring data" (Supply Chain Manager, Shipper, Food, SME).

SMEs also reported being more interested in improving flexibility than LEs. Flexibility is mainly connected to the ability to reconfigure the logistics system quickly and at a lower cost; this is pursued mainly thanks to the exchange of real-time information among different actors. One example found in the interview study is the replanning of unloading activities based on

real-time truck delays and estimated arrival times, shared via digital platforms. While only a few firms reported it, some also cited environmental and social sustainability performance as a motivation for adopting L40 solutions, reinforcing the idea that there is a link between sustainability and L40.

5 Discussion

5.1. Sizing Effects

The main aim of our research is to investigate the current diffusion of L40 practices, concerning the maturity of the L40 solutions implemented, and to understand whether - and if so, how - firm size plays a role in driving it. Results showed that firm size does not seem to significantly affect the diffusion of L40: both LEs and SMEs are successfully implementing L40 solution. Moreover, size is not always directly related to an advancement in the maturity level of the technology adopted, in terms of value offered (i.e. horizontal maturity): while a higher percentage of LEs reached stage 2 on average, a higher percentage of SMEs reached stage 3 on this dimension. Instead, size seems to have an impact on how firms are shaping the diffusion of L40 solutions. LEs tend to initiate the L4.0 diffusion with the Automation principle, and their path is largely driven by automation. LEs are investing in hardware-based technologies, such as advanced robotics and autonomous vehicles, supporting mainly warehouse operations. These technologies are applied at a single firm level with the main objective of achieving higher process efficiency through the automation of physical operations such as picking, sorting or packing. LEs also seek to reduce errors in internal operations and improve time performance, expressed as speed of operations. Once the benefits of Automation are realized, LEs tend to add the Integration principle, sharing the data collected from the automation as a by-product with other business functions or other business partners. On the other hand, the research reveals that most SMEs are approaching L40 starting from the Integration principle, meaning that they are investing in technologies that enable vertical and horizontal integration, mobile-based systems, and digital platforms that facilitate the sharing of information among different actors in the supply chain. These technologies are used to connect with other supply chain partners to improve the communication and the efficiency of interface processes such as ordering, shipping and loading/unloading. In this regard, the study also reveals that interfirm-relationships act as a key driver for L40 diffusion among SMEs, with supply chain actors pushing SMEs to provide greater visibility on their logistics processes (Asare, Brashear-Alejandro and Kang, 2016; Mathauer and Hofmann, 2019). Integration technologies help SMEs gain better control over the logistics process, resulting in improved

quality; time benefits are also observed, as SMEs can provide accurate information to the right recipients in real-time, improving the service level. Additionally, flexibility performance is enhanced, since the data collected and shared can be used to reconfigure processes, such as shipping, at the minimum cost. For most SMEs, the development path of L40 starts from the Integration principle and can follow two directions. It may progress towards the Automation principle, which SMEs approach differently from LEs – rather than investing in advanced automation or autonomous vehicles, SMEs tend to adopt IoT technologies to automate data acquisition – or the path may move towards the Intelligence principle, where SMEs capitalize on the data collected and shared by investing in technologies for data analysis.

These differences lead us to define two distinct roles that firms appear to assume in the digital transformation of logistics processes. We refer to them as "Automators", arising from LEs, and "Integrators", arising from SMEs. Table VII summarises the features of these two groups.

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Table VII - Firms' role according to size

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Starting their L4.0 diffusion primarily with the Automation principle and investing in hardware-based technologies, such as advanced robotics and autonomous vehicles supporting warehouse and transportation processes, LEs serve as the Automators in the digitalization of logistics and supply chain processes. Conversely, SMEs ac as the Integrators in the digital transformation of logistics and supply chain processes, by providing network connectivity among various supply chain actors.

These roles align with the characteristics of the two groups. Acquiring hardware-based technologies implies a significant financial burden (Mathauer and Hofmann, 2019), and only firms with substantial financial power, a characteristic typically associated with LEs, can afford such investments. The large investments required to acquire technologies may be supported by government incentives, which seem to benefit LEs mainly, as shown by the research results. This provides further evidence of the ability of LEs to attract funds. On the other hand, the technologies associated with the L40 development path of SMEs typically require lower financial investment (Culot et al., 2020), which aligns with the generally lower financial capacity of SMEs compared to LEs. Moreover, these technologies help increase the responsiveness and flexibility of the supply chain, reinforcing the main strength associated with SMEs (Evangelista and Sweeney, 2006; Ali et al., 2023).

5.2. Theory Development

For developing logistics and operations management theory further based on these observed size effects regarding firms reacting and strategizing in the wake of L40 developments, we draw on the Theory of Constraints (TOC) (Rahman, 1998), outlining that every productive operations system must have at least one constraint. Although this is basically modelled on manufacturing systems, it applies to logistic systems in the same fashion as the same logic of resources, limitations and outputs applies. A constraint in this sense is constituted by anything that prohibits a system from achieving higher performance levels (Goldratt, 1990). Furthermore, and most importantly, this existence of constraints represents future opportunities for improvement. Contrary to conventional thinking, TOC views constraints as distinctively positive, not per se negative. Because constraints determine the performance of a system, a gradual elevation of the system's constraints will potentially improve its performance (Mabin & Balderstone, 1999). This theory venue is still under constant development and extended towards many directions and applications (McCleskey, 2020).

Now, if such constraints not only exist inside one system, but are potentially intertwined across individual firms in production systems, this notion would be the perfect explanation of what we recognize in the case of L40 adoption for different clusters of firms. It has become obvious, that smaller firms strategize and act distinctively differently from their larger size counterparts. This could well be connected – although we have no further empirical knowledge to support this hypothesis at this moment but would require further research – to the fact that there are different constraints applicable to the two groups of firms: whereas smaller firms typically lack the ability to put up larger amounts of investment sizes in terms of technology and R&D invest, larger firms oftentimes lack the agility and innovation potential to develop new processes and services in an agile and fast pace.

Given this setting, we develop a theory discourse and contribution labelled "interconnected constraints", indicating that the existing constraints for one firm (belonging to one of the smaller or larger firm size groups) are connected to the constraints of another firm (belonging to the other group and vice versa) in at least two ways: first, the individual constraint is usually not existent with the firm member of the other group, they are therefore mutually exclusive. Second, they are furthermore complementary in this sense, that a potential development or collaboration of one firm could actually alleviate the constraint of the other (from the other group). This can be exemplified as follows: as the larger firm typically has severe constraints in fast and agile process adaption and innovation, it might well collaborate with a smaller firm

and therefore profit from their freedom of exactly that constraint. The same is true for the smaller firm, typically lacking larger investment budgets – therefore through a close collaboration the smaller firm could potentially access the larger investment funds of the large-sized firm. This interconnected nature is depicted in Figure I for the example of two firms A and B, and can partly explain the complementary nature of the L40 implementation strategies we find in the empirical observation during this study. As seen in the figure, one firm (A) might have a typical constraint (e. g. typical for small and medium-sized firms like investment budget constraint) that is potentially balanced by the other firm (B) not having exactly this constraint – whereas the second firm (B) might have another form or areas of constraint (e. g. typical for large-sized companies as a lack of flexibility of agility) which could be mitigated by the capabilities of the first Firm A. In this sense both firms might decide to develop their L40 capabilities in relation to each other, each focusing on the strengths of each and therefore helping each other in balancing their interconnected constraints in order to achieve innovation.

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Figure I – Concept of Interconnected Constraints

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6 Conclusion and Outlook

Despite the current hype surrounding L40, the existing literature provides limited insights into the industry's state-of-the-art L40 diffusion rate. Moreover, the role of factors such as firm size in driving the successful diffusion of L40 and how firms embark upon digital transformation are still open issues. Our study is one of the first empirical studies to advance this debate by offering an extensive overview of the diffusion rate of L40 in Italy and exploring how firms contribute to the digitalization of logistics and supply chain processes based on their size. Our main findings indicate that firms are successfully adopting L40 technologies and solutions for their processes, but the maturity of the technologies and solutions implemented remains low. Moreover, our research highlights that firms shape their digital transformation differently according to their size. We identified two main roles: Automators, referring to LEs that invest in hardware-based automation technologies to enhance process efficiency, and Integrators, referring to SMEs that focus on integration technologies to improve process quality and flexibility. Understanding how firms approach their investments in L40 may be a critical success factor to transform opportunities from L40 into a competitive advantage and to

facilitate the transition of logistics and supply chain processes toward the fourth industrial paradigm.

6.1. Theoretical contributions

Several authors have discussed I40 diffusion in manufacturing worldwide (see for example Masood and Sonntag, 2020; Wamba and Queiroz, 2020; Ardolino et al., 2022). Nevertheless, L40 diffusion has received less attention and its diffusion rate remains unclear. Our study contributes to this debate, providing empirical insights from 65 Italian firms from the perspectives of the maturity of L40 solutions, together with the type of L40 technology adopted, target areas, adoption drivers, and performance improvements. The state-of-the-art investigation shows that L40 has achieved a good diffusion rate among Italian firms, but the maturity of implemented solutions remains low. From a Horizontal maturity perspective, most firms are using technologies for Visibility & monitoring (66% corresponding to 43 firms). From a Vertical maturity perspective, 75% of firms (corresponding to 49 firms) are utilising only one of the three core L40 principles: Automation, Integration, and Intelligence. We conclude that while Italian firms are aware of L40 and are transitioning toward it, the journey is ongoing, and maturity is far from being achieved. This is in line with findings from other studies about I40 diffusion, which shows that the 4.0 adoption is gradually increasing over time (e.g Ardolino et al., 2022), and that digital transformation is a continuous process (Cichosz, Wallenburg and Knemeyer, 2020). For what concerns the type of L40 technologies adopted, our study shows that advanced automation technologies, vertical and horizontal integration technologies, and mobile-based systems are the most diffused. Warehouse management emerges as the main target area for L40 applications, reinforcing Winkelhaus and Grosse (2020) findings, which highlight that warehousing represents one of the pioneering tasks for the digital transformation of logistics processes. Our study highlighted the inclusion of L40 as a strategic objective and the ease of technology implementation as key drivers of L40 diffusion, and therefore confirms results obtained by previous diffusion studies (e.g. Rogers, Singhal and Quinlan, 2019). his strengthens the argument that L40 adoption is a strategic decision, and that reservations at the top management level can hinder its implementation. Moreover, the usability of the technology plays a crucial role in its successful diffusion.

Concerning the factors influencing L40 diffusion, our research contributes to the debate around the role of firm size in technology adoption and organizational innovativeness, by investigating whether and how firms of different sizes are implementing L40. Unlike other studies (Ardolino

et al., 2022), our research indicates no significant difference in the diffusion rate or maturity of L40 technologies and solutions adopted between LEs and SMEs, at least concerning logistics. This supports the view that firm size alone does not dictate innovation diffusion and firm innovativeness, but other drivers related to firm size explains this relationship (Ahuja, Lampert and Tandon, 2008). Our study reveals that LEs and SMEs are shaping their digital transformation paths differently based on their characteristics. LEs leverage their financial resources and their ability to attract funds, such as government incentives, to invest in hardware-based, capital-intensive technologies like advanced automation and autonomous vehicles, to improve the efficiency of their logistics processes. In contrast, SMEs are investing in technologies aligned with the Integration principles, including vertical and horizontal integration technologies, digital platforms, and traceability systems. Being primarily software-based, these technologies are less capital-intensive, but they require the transformation of the network structures and process re-engineering to achieve the desired improvements (Patrucco, Ciccullo and Pero, 2020). This may be easier for SMEs to accomplish, given their relatively simple and flexible organizational structure (Evangelista and Sweeney, 2006). These technologies are mainly implemented to improve process quality, responsiveness, and flexibility. We can therefore say that LEs and SMEs seem to be leveraging their core strengths to shape their digital transformation journeys: LEs exploit their financial power and reliability to advance L40, while SMEs utilize their flexible structure and strong cross-functional communication and interaction capabilities to introduce technologies that integrate processes and information across supply chain partners. Moreover, our research highlights that LEs and SMEs are adopting L40 to support and enhance their main source of competitive advantage: LEs focus on technologies and solutions that allow them to improve their efficiency and their productivity, thus boosting the benefits deriving from economies of scale, while SMEs invest in technologies and solutions that enhance the quality of their processes, and support their responsiveness and their flexibility.

Given these differences, we identified two distinctroles that firms play in the digital transformation of logistics processes: Automators (Les), and Integrators (SMEs). These roles reflect the unique characteristics of LEs and SMEs and how firm size influences L40 diffusion. Based on our findings and expertise, we believe that both aspects are essential for transforming logistics and supply chain processes and benefit from the fourth industrial paradigm. The process efficiency gained through the introduction of L40 automation technologies, primarily driven by LEs, can benefit other supply chain actors by improving productivity and reducing costs. Meanwhile, the integration capabilities offered by SMEs promote communication and

collaboration across the supply chain, helping to achieve the expected benefits of L40 for all involved actors.

Based on this, the new theory element of “interdependent contraints” was developed related to the original Theory of Constraints in the discussion part of this paper.

6.2. Managerial implications

This paper extends the knowledge regarding L40 diffusion and its relationships with firm size. The results offer several practical insights for logistics firms and practitioners. First, our research shows the main 4.0 technologies successfully adopted by firms, and their diffusion rate, providing a set of mature and established technologies within the L40 paradigm. This can help 4.0 beginners or more conservative firms reduce their skepticism towards innovation and better target their investment effort, thereby accelerating L40 diffusion among firms. Moreover, the data on L40 technologies diffusion reflect the attractiveness of these technologies, offering valuable feedback to technology providers regarding overall industrial interest in L40 solutions. Second, the study of L40 diffusion target areas and drivers provides a reference point for practitioners and helps logistics and supply chain managers as they approach L40 implementation. The results suggest that certain target areas could particularly benefit from L40 adoption, while identifying gaps where its diffusion is less established, thus helping managers focus their efforts on transitioning to L40. Moreover, results show that integrating L40 into a firm’s overall strategy facilitates its successful introduction and that the usability of chosen technology has a significant impact, either positive or negative, on the adoption process. Third, the research demonstrates that firms experience increased efficiency, quality, and flexibility from adopting I4.0 technologies. This could encourage firms to implement L40 in more processes, expanding the scope of their applications and refining their technology strategies to gain a competitive advantage. Last, our findings provide indications for managers regarding how firms of different sizes embrace digital transformation. For LEs, it is recommended to leverage their greater financial capacity to invest in advanced automation technologies, while ensuring that they remain agile in integrating these technologies across their supply chain. LEs should consider complementing their automation investments with integration solutions to enhance real-time data sharing and optimize inter-firm collaboration. Additionally, as LEs often face challenges in rapid innovation, partnerships with smaller, more flexible firms can provide access to new processes and innovation capabilities, helping them overcome constraints in agility. For SMEs, the findings suggest focusing on integration technologies that improve communication and collaboration across the supply chain. By

adopting solutions that enhance visibility and real-time data exchange, SMEs can increase their responsiveness and flexibility, helping them stay competitive despite lower financial resources. SMEs can further benefit from exploring data analytics and intelligence tools, using the data generated through integration technologies to improve decision-making processes. Collaborating with larger firms can provide SMEs access to advanced automation technologies, allowing them to enhance their digital transformation journey without shouldering the full financial burden. L40 represents both a new opportunity for investment and innovation and a challenge to remain competitive in today's dynamic and complex environment. As firms often struggle to successfully embark on digital transformation due to doubts and misconceptions around L4.0 (Mathauer and Hofmann, 2019), our findings offer guidance on how to begin their transition journey towards L40 implementation, or how to take further steps. Moreover, managers can use our results to benchmark their firm's progress against other firms with similar characteristics.

6.3. Limitations and future research directions

Our research presents some limitations that open up avenues for further research. First, the explanatory power of the study is limited by the sample size, the high specificity of individual L40 technologies and solutions, and the focus on the firm size as the only moderating effect for L40 diffusion. Moreover, the focus on Italian logistics firms may limit the degree to which the findings could be generalized to other countries. Future research could improve the empirical validation of the results by expanding the study to a larger sample, potentially extending the research to firms in other countries, both developed and developing, to confirm the roles of the firms identified in this study. Second, we focus our attention on firm size affecting L40 diffusion, thus neglecting other variables that can influence the firms' behaviour, such as external market conditions, macroeconomic situations, or specific cost-benefit analyses. Future studies could explore how these factors interact with firm size to influence the diffusion of L40. Third, due to the exploratory nature of the study, we adopted broad categories to define L40 diffusion, linking it to the degree of transformation an L40 solution provides to logistics processes and the maturity of the L40 technology in supporting digital transformation. While we believe this approach has merit, offering a more strategic perspective on the overall L40 paradigm, future research could narrow the scope by examining specific L40 technologies and their individual impacts. Lastly, L40 is a dynamic and rapidly evolving trend, with new developments and solutions continually emerging. We, therefore, see the value in follow-up studies to determine whether L40 diffusion and the maturity of the solutions investigated in this study change over time.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table I - Sample charatcetistics

		n°	%
Firm size	LEs	34	52
	SMEs	31	48
Firm type	LSP	14	22
	Manufacturer	39	60
	Retailer	12	18
Industrial sector	Cosmetics & Personal Products	2	3
	Electronics & Components	2	3
	Entertainment	1	2
	Fashion	8	12
	Food	26	40
	Health Care	9	14
	House Durables	7	11
	Industrial & Machinery	6	9
	Multi-industry	4	6
Interviewee role	CEO	4	6
	COO	4	6
	Innovation Manager	2	3
	Logistics Manager	27	41
	Marketing Manager	6	9
	Operations Manager	1	2
	Supply Chain Manager	20	31
	Transportation Manager	1	2

Table II – Codes definition

Aggregate dimensions	II order themes	I order concepts	References
L40 technology	Advanced automation technologies	• Collaborative robot • Exoskeleton • Robots • Robot-based solutions (e.g. automated vehicle storage and retrieval system, vertical robotic storage and retrieval system)	Winkelhaus and Grosse, 2020
	Autonomous vehicles	• Automated guided vehicles (AGV) • Drones • Laser-guided vehicles (LGV)	
	Internet of Things (IoT)	• RFID tag • IoT sensors • Satellite trackers and GPS sensors	
	Mobile-based systems	• Proprietary logistics applications • Web-based applications	
	Vertical integration and horizontal integration	• Transportation Management Systems (TMS) • Warehouse management systems (WMS) • Electronic data interchange (EDI)	
	Digital platforms	• Collaborative proprietary platforms • Web-based platforms	
	Advanced analytics	• Big Data Analytics (BDA) • Digital Twin (DT) • Artificial intelligence (AI)	
Target areas	Warehouse management	• Packing • Picking • Sorting • Storage and Retrieval • Warehouse planning	Winkelhaus and Grosse 2020; Patrucco, Ciccullo and Pero, 2020;
	Transportation management	• Loading/unloading • Shipping • Transportation planning	
	Stakeholder coordination	• Communication • Documents sharing • Decision making	
	Human resources management	• Shift management • Human resources planning	
Diffusion drivers	Requirements from other supply chain partners	• Required from customers • Required from suppliers • Required from logistics service providers	Lin *et al.*, 2018; Mathauer and Hofmann, 2019; Rogers, Singhal and Quinlan, 2019; Kiraz *et al.*, 2020; Mahmood and Mubarik, 2020; Moeuf *et al.*, 2020; Orji *et al.*, 2020; Raj *et al.*, 2020; Chauhan, Singh and Luthra, 2021; Kinkel, Baumgartner and Cherubini, 2022
	Governmental incentives	• National government incentives • Other governmental incentives	
	Strategic objective	• Bottom-up approach • Top-down approach • Digitalization strategy • Ad-hoc roles	
	Enhancing data availability and quality	• Data availability • Data reliability • Enhanced decision making	
	Outdated machinery	• Fault machinery substitution • Old machinery substitution • Outdated software and IT systems substitution	
	Ease of technology implementation	• The technology is easy to understand • The technology is easy to use • The benefits of the technology are clear • The technology is seamlessly integrated into logistics processes	
	Competitiveness	• Adoption of L40 solutions by competitors • Enhance the competitive advantage	

Performance improvement		Efficiency	• Reduce cost • Improve resource productivity • Improve process efficiency • Improve communication efficiency	Winkelhaus and Grosse, 2020; Hopkins, 2021; Within case
		Time	• Operational speed • Service level	
		Quality	• Reduce errors • Improve process and product reliability	
		Flexibility	• Process reconfiguration • Resources reconfiguration	
		Environmental sustainability	• Waste and resources reduction • CO_2 emissions reduction	
		Social sustainability	• Workers well-being • Ergonomics	
L40 solution maturity	**Vertical maturity**	Automation	• Data acquisition is performed with minimum human assistance • Data acquisition is performed with no human assistance • Data acquisition happens in real-time • Operations are performed with minimum human assistance • Operations are performed with no human assistance	Modica *et al.*, 2021
		Integration	• Data sharing is performed with minimum human assistance • Data sharing is performed with no human assistance • Data are available to the whole firm • Data are available to one supply chain partner • Data are available to all supply chain partners	
		Intelligence	• Operational decisions • Tactical decisions • Strategic decisions • Decentralized decision making	
	Horizontal maturity	Visibility and Monitoring	• Data collection • Data sharing • Remote process monitoring • Traceability	Fettermann *et al.*, 2018; Modica *et al.*, 2021
		Planning and Control	• Resources planning • Transportation planning • Warehouse planning • Supply chain planning • Process control • Quality control • Resources control	
		Predictability and Optimization	• Optimization of operations • Optimization of resources • Forecasting • Scenario analysis	
		Self-organization and Adaptability	• Learn from the environment • Adapt to the environment • Autonomous set-up • Improve performance	

Table III – Research results on L40 horizontal maturity by firm size

		SMEs		LEs	
		n°	**%**	**n°**	**%**
Horizontal maturity	**Visibility & Monitoring**	23	**74**	21	**62**
	Planning & Control	3	**10**	9	**26**
	Predictability & Optimization	5	**16**	4	**12**
	Self-organization & Adaptability	0	**0**	0	**0**

Table IV – Research results on L40 vertical maturity by firm size

		SMEs		LEs	
		n°	**%**	**n°**	**%**
Vertical maturity	**Automation**	9	**29**	15	**44**
	Integration	13	**42**	7	**21**
	Intelligence	4	**13**	1	**3**
	Automation + Integration	3	**10**	6	**18**
	Automation + Intelligence	0	**0**	2	**6**
	Integration + Intelligence	2	**6**	3	**9**
	Automation + Integration + Intelligence	0	**0**	0	**0**

Table V - Research results on L40 technologies by firm size

		SMEs		LEs	
		n°	**%**	**n°**	**%**
L40 tecnology	**Advanced automation**	5	**16**	14	**41**
	Autonomous vehicles	1	**3**	7	**21**
	Internet of things (IoT)	3	**10**	7	**21**
	Mobile-based systems	6	**19**	8	**24**
	Vertical integration and horizontal integration	10	**32**	8	**24**
	Digital platforms	4	**13**	3	**9**
	Advanced Analytics	6	**19**	5	**15**

Table VI – Research results on performance improvement by firm size

		SMEs		LEs	
		n°	**%**	**n°**	**%**
Performance improvement	**Efficiency**	18	**58**	23	**68**
	Time	11	**35**	14	**41**
	Quality	16	**52**	14	**41**
	Flexibility	5	**16**	1	**3**
	Environmental sustainability	1	**3**	1	**3**
	Social sustainability	0	**0**	1	**3**

Table VII – Firms' role according to size

Variable		**Automators**	**Integrators**
Firm size		LE	SME
L40 solution maturity	**Horizontal maturity**	Not differential	Not differential
	Vertical maturity	Automation driven	Integration driven
L40 technology		Firms-oriented, hardware-based technologies	Connectivity-oriented, software-based technologies
Performance improvement		Internal operations efficiency, Quality of internal operations, Speed of internal operations	Interface processes efficiency, Efficiency of communication, Process control, Service level, Flexibility

Figure I – Theory Concept of Interconnected Constraints