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Logistics 4.0 measurement model: empirical validation based on an international survey

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Abstract

Purpose – This study aims to provide a measurement model, and the underlying constructs and items, for Logistics 4.0 in manufacturing companies. Industry 4.0 technology for logistics processes has been termed Logistics 4.0. Logistics 4.0 and its elements have seen varied conceptualizations in the literature. The literature has mainly focused on conceptual and theoretical studies, which supports the notion that Logistics 4.0 is a relatively young area of research. Refinement of constructs and building consensus perspectives and definitions is necessary for practical and theoretical advances in this area.

Design/methodology/approach – Based on a detailed literature review and practitioner focus group interviews, items of Logistics 4.0 for manufacturing enterprises were further validated by using a large-scale survey with practicing experts from organizations located in Central Europe, the Northeastern United States of America and Northern Thailand. Exploratory and confirmatory factor analyses were used to define a measurement model for Logistics 4.0.

Findings – Based on 239 responses the exploratory and confirmatory factor analyses resulted in nine items and three factors for the final Logistics 4.0 measurement model. It combines “the leveraging of increased organizational capabilities” (factor 1) with “the rise of interconnection and material flow transparency” (factor 2) and “the setting up of autonomization in logistics processes” (factor 3).

Practical implications – Practitioners can use the proposed measurement model to assess their current level of maturity regarding the implementation of Logistics 4.0 practices. They can map the current state and derive appropriate implementation plans as well as benchmark against best practices across or between industries based on these metrics.

Originality/value – Logistics 4.0 is a relatively young research area, which necessitates greater development through empirical validation. To the best of the authors knowledge, an empirically validated multidimensional construct to measure Logistics 4.0 in manufacturing companies does not exist.

Keywords Logistics 4.0, Manufacturing, Scale development, Survey, Factor analysis

Paper type Research paper

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1. Introduction

Logistics in manufacturing firms consists of planning, implementing, and controlling the flow and storage of goods as well as services from the point of external origin to the company and from the company to the point of consumption to fulfill customer requirements (Lummus *et al.*, 2001; Tang and Veelenturf, 2019). Globalization of markets, demographic change, shortening product lifecycles, increased customer demands to offer individualized products by considering sustainability aspects are current challenges of production and logistics systems (Kagermann *et al.*, 2013; Lasi *et al.*, 2014; Jubiz-Diaz *et al.*, 2019). Moreover, saturated markets and new customer demands put pressure on logistics systems (Bauernhansl, 2014). Therefore, new ways of production and logistics are needed to avoid an increase in costs and competitive disadvantage of manufacturing companies (Hofmann and Rüsch, 2017).

Industry 4.0 digitization and automation seeks to merge information technology (IT) with production and logistics processes (Kagermann *et al.*, 2013; Xu *et al.*, 2018; Woschank *et al.*, 2020a). One of the main objectives of Industry 4.0 is to reach the mass customization production paradigm (Kagermann *et al.*, 2013), by combining the scale effects of mass production with the scope effect of individualized products (Lasi *et al.*, 2014; Barman and Canizares, 2015). Therefore, a corresponding system for logistics is needed that guarantees proper material and information flows in manufacturing companies.

Based on a recent survey performed by Deloitte, Industry 4.0 based technology initiatives have been mainly concentrated on operations in manufacturing and many enterprises undervalue the strategic role of logistics as a competitive lever (Deloitte Insights, 2018). Industry 4.0 technology and concepts applied to industrial logistics have resulted in the term *Logistics 4.0* (Barreto *et al.*, 2017; Müller and Voigt, 2018). But the term Logistics 4.0 – similar in many ways to its parent Industry 4.0 (Chiarello *et al.*, 2018) – lacks a consensus definition and set of constructs (Szymańska *et al.*, 2017).

Some studies – for example, Strandhagen *et al.* (2017) – define Logistics 4.0 with a variety of characteristics, like, real-time big data analytics (BDA), innovative manufacturing leading to reduced storage requirements, autonomous robots for optimized inventory control, and real-time information exchange. Others delineate Logistics 4.0 on general terms such as transformation from hardware-oriented logistics to software-oriented logistics (Timm and Lorig, 2015). Logistics 4.0 as a logistical system enabling individualized customer demand satisfaction without cost increase while getting support from industry and trade digital technologies is another set of definitional dimensions (Winkelhaus and Grosse, 2020). Additionally, real-time tracking of material flows, supply chain transparency and flexibility, have been put forward as Logistics 4.0 elements (Hofmann and Rüsch, 2017). These definitions and characteristics are only recent examples of the many different conceptual elements, technologies, and enablers of Logistics 4.0 proposed in the literature (Burow *et al.*, 2018; Evtodieva *et al.*, 2019).

Most studies are still relatively conceptual and theoretical. These characteristics indicate a relatively immature Logistics 4.0 research and practice, which necessitates some form of empirical validation to advance Logistics 4.0 science and practice (Winkelhaus and Grosse, 2020). Additionally, Industry 4.0 has received the greatest attention with increasing systemic research investigation. Logistics 4.0, however, is greatly lacking in investigation (Winkelhaus and Grosse, 2020).

In practice, manufacturing companies will benefit from a validated Logistics 4.0 measurement model by obtaining a concise definition and, therefore, well-defined constructs and indicators that will help them in the structured implementation of Industry 4.0 in logistics. From a management point of view, they can, based on the use of the Logistics 4.0 measurement model, determine their current status as well as compare it with best-in-class companies. Based on these assessments, it is possible to derive and ultimately implement actions for a holistic implementation of Industry 4.0 in logistics.

From a scientific point of view, empirically validated measurement models for Logistics 4.0 are still missing in the literature (Bag *et al.*, 2020). However, these measurement models would contribute significantly to the enhancement of theory, especially concerning the usage of Industry 4.0 in logistics, and thus significantly promote the understanding of causal relationships in logistic systems. For this reason, this study aims at the systematic development and validation of a measurement model for Logistics 4.0 and its underlying constructs and indicators.

Using an exploratory and confirmatory factor analysis and a large-scale empirical survey, this study aims to develop a Logistics 4.0 measurement model. The initial items development used a literature review and various focus group interviews. The validation has been performed by a large-scale survey of experts from Central Europe, the Northeastern United States of America (US), and Northern Thailand.

The paper proposes an empirically validated first- and second-order measurement model for Logistics 4.0 and thus it contributes to theory by better defining Logistics 4.0. The aim of this paper is to answer the following research question:

RQ1. What are the main scale items and appropriate factors to assess Logistics 4.0 in manufacturing companies?

The remainder of the paper is organized as follows. The second section of the paper reconciles the results of the focus group interviews and the scientific literature. The third section describes the research methodology. The fourth and fifth sections describe the results of the study to answer the research question; implications, limitations, and future research directions are also identified.

2. Related works

The first step in building this evaluation is to determine and analyze related studies. This sets the scholarly and theoretical foundation for additional inputs from experts. A review of the literature has been completed and the main findings are summarized. The categorization of the identified studies is based on a grounded theory approach (Böhm, 2000; Breuer, 2010). The coding – respectively the definition of the categories – is established by importing qualitative data, creating preliminary categories, reviewing their convergent or divergent relationships, and redefining the final key categories within a circular approach (Equit and Hohage, 2016).

2.1 New process standardization and organization models

Gomes *et al.* (2018) evaluated and prioritized the components of Industry 4.0 using expert surveys. Terms of attributes and technologies that influence the organizational interoperability of automotive supply chains were the focus. As Industry 4.0 technology enablers, 3D-printing, mobile robotics, analytics, cloud, and machine-to-machine were identified, while, as attributes, connected supply chain, extended innovation, agile collaboration network, smart services, decentralized production control, connected lifecycle innovation, data-driven operational excellence, and smart products were investigated. In this direction, Chandriah and Raghavendra (2019) proposed an architectural framework to implement Industry 4.0 in supply chains for the automotive industry, which is composed of a cloud ecosystem for diagnostics and car maintenance. Similarly, Iordache (2017) discussed reference architectures (e.g. the reference architectural model industry 4.0 – RAMI 4.0) as a prerequisite of the Industrial Internet of Things (IIOT).

Doh *et al.* (2016) emphasized the adaptation of the lean philosophy with its focus on efficiency, effectiveness, and waste reduction based on customer orientation. In sum, the change management processes to reach Industry 4.0 readiness should focus on the following three areas: 1) man-machine interaction, 2) technology (information and communication technology (ICT) and sensors), and 3) organization.

Kai *et al.* (2017) described cell-level collaborative production-logistics systems as an enabler for multi-variety and small-batch production. The proposed system enables the possibility to deal with a large number and/or frequent changing orders dynamically by using existing resources and production capability.

Dallasega *et al.* (2018) investigated to what extent Industry 4.0 concepts can optimize proximity between actors in the construction supply chain. It emerged that Industry 4.0 concepts have a significant influence on technological, organizational, geographical, and cognitive dimensions of proximity. According to the results, improved connectivity facilitates collaboration by giving supply chain actors access to data through ERP systems, web-based portals, and mobile Internet-enabled devices. Similarly, Radio Frequency Identification (RFID) in combination with Geographic Information System (GIS) facilitates the use of data to track products and localize components. The use of RFID also facilitates the collection of real-time data to monitor processes and make production control more responsive.

2.2 Industry 4.0 fostering sustainability in logistics

Bhagawati *et al.* (2019) investigated the sustainability of an automotive supply chain with a focus on Industry 4.0-related performance factors. Thirteen performance factors were identified: the Internet-of-things (IoT), environment, operational management, supplier management, economic, logistics integration, cyber-physical systems (CPS), customer response adoption, social, cost management, time management, strategic sourcing, and service management.

Manavalan and Jayakrishna (2019) proposed a framework for assessing sustainability in supply chain management from an Industry 4.0 perspective using five areas, namely, business, technology, sustainable development, collaboration, and management strategy. The proposed framework is based on theoretical literature, and it is generic for all organizations.

Luthra *et al.* (2019) investigated Industry 4.0 drivers to diffuse sustainability in supply chains. Government supportive policies along with collaboration and transparency among supply chain members were identified as highly significant drivers of Industry 4.0.

2.3 Advanced planning and data analysis systems

Burow *et al.* (2018) reported that data from equipment, control systems, legacy systems, products, complex industrial designs, and distribution networks need to be processed, analyzed, and shared seamlessly, safely, and under real-time constraints.

Alias *et al.* (2017) identified adaptive processes and supporting information systems as drivers of technological innovation within the evolving area of Industry 4.0. This should be supported by new hardware equipment (e.g. robotics, cyber-physical systems, sensors, advanced materials) and new software solutions for an intensified digitalization based on heterogeneous sources of information, higher volumes of data, increasing processing speed, and new data types. In this direction, recent works investigated the usage of real-time data in production planning and control of manufacturing and the impact on logistics performance indicators (Woschank *et al.*, 2020b; Woschank and Dallasega, 2021).

Furmann *et al.* (2017) discussed the concept of the digital twin in logistics able to create an environment of the digital factory in which the company can optimize the logistics system directly by changing the parameters and configurations in real-time. Similarly, Kaiblinger and Woschank (2022) analysed the state of the art and future directions of digital twins for production logistics.

In this direction, Dallasega *et al.* (2019) presented a decentralized and agile scheduling and control approach suitable for ETO construction supply chains. By using a discrete event simulation, they demonstrated that real-time data, made available by Industry 4.0 technologies, have a high potential to sense and react to plan deviations as soon as they appear. Similarly, Lv and Lin (2017) proposed a real-time operation planning system suitable for large, distributed manufacturing networks. The approach was validated by using simulation, proving that it can reduce the traditional planning workload while improving the planning results without manual error interference.

Gottge *et al.* (2020) investigated the practical impact of big data, the Internet of Things, and business intelligence on the purchasing process of premium automotive manufacturers. The main changes of both, strategic and operative purchasing processes were caused by the automated prequalification, the co-creation of specifications, interactive call-offs, proactive troubleshooting, and parameter-based negotiations. Thus, transaction costs were decreased thanks to reduced uncertainty and supplier specificity, as well as by lowered information search, negotiation, and monitoring costs.

2.4 Modern ICT enabling smart supply chains

Kucukaltan *et al.* (2022) investigated how logistics service providers (LSP) can take advantages of using Industry 4.0 technologies by considering operational, financial, and human resources/workforce aspects.

Kovacs and Kot (2016) discussed various trends and challenges of intelligent logistics, where the following five main components were outlined: (1) digital workpieces, (2) intelligent machines, (3) vertical network connection, (4) horizontal network connection, and (5) smart workpieces. Logistics 4.0 should be enabled by the integration of horizontal and vertical value chains, by the digitalization of products and services, and by the formation of digital business models and customer relations.

Schulz and Freund (2018) presented requirements for a decentralized enterprise information processing system and a reference model of Industry 4.0 distributed supply chains. They discussed how blockchain technology (as one of the Industry 4.0 technologies) can contribute to improving supply chains by providing trusted interactions without a central authority or intermediaries, a distributed storage capability, and interoperability on a distributed supply chain.

Sorger *et al.* (2021) presented a logistics- and production-orientated approach to a systematic digitalization of manufacturing enterprise by focusing on the usage of Big Data in the metal processing value chain.

Valente and Neto (2017) outlined the importance of intelligent tracking of products by using Internet of Things (IoT) and radio-frequency identification (RFID) technologies as the main enablers for end-to-end processes to improve productivity in the entire value chain. According to the authors, it is important to use standardized reference frameworks for the automated communication of smart objects within the production logistics system.

Bonavolonta *et al.* (2017) reported on the requirement of key technologies, such as IoT, the availability of cost-effective sensing and/or computing elements as well as the ad-hoc communication protocols as the main enablers of Industry 4.0 in supply chains.

Gupta *et al.* (2020) identified key digitization technologies that can improve supply chain performance. According to their results, *"big data/data science skills"*, *"tracking and localization of products"* and *"appropriate and feasibility study for aiding the selection and adoption of big data technologies and techniques"* are the main digitization and IT enablers that companies should focus on improving their supply chain performance.

Barreto *et al.* (2017) discussed the application of new information and communication technologies as the main enablers of Industry 4.0. They reported on the Industrial Internet of Things (IIOT) as enabling high transparency as well as supply chain visibility. According to the authors, IIOT enables integrity control, which means that the right products arrive at the right time, to the right place, in the right quantity, and at the right costs.

Schniederjans *et al.* (2020) performed a large-scale literature review as well as a textual analysis to uncover supply chain digitization trends. It emerged that healthcare and food supply chains are the most prevalent industries. Logistics, as well as customer relationship management, are the most prevalent topics considered in both scholarly and practitioner' publications. Moreover, IoT and big data were categorized as the most prevalent technologies in the field of supply chain digitization. IoT, big data, and cloud computing were forecasted as continuing to grow in the coming years.

Dunke *et al.* (2018) discussed the relevance of time and uncertainty in the context of supply chain planning. They show the impact of new technological developments in the field of Industry 4.0 and how online optimization models can cope with real-time challenges in the field of supply chain planning.

Ivanov *et al.* (2018) proposed a conceptual framework that investigates the relationships between big data analytics, additive manufacturing, advanced trace and tracking systems, and supply chain disruption risks. According to the study results, Industry 4.0 technologies increase demand responsiveness, capacity flexibility, inventory control, as well as supply chain visibility. Similarly, Doh *et al.* (2016) reported on the usage of intelligent information processing techniques (e.g. new ICT technologies based on RFID) as system integrators of Lean Manufacturing to meet Industry 4.0 requirements. More in detail, Evtodieva *et al.* (2019) report that intelligent supply chain management consists of the following concepts and technologies: predictive analytics for demand forecasting, artificial intelligence for warehouse management, chatbots in procurement, intelligent transportation systems, location tracking systems, and cybersecurity systems.

2.5 Automated vehicles and logistic systems

The main enablers to cope with the challenges of future logistics operations can be defined as enhanced material flow systems (Hofmann *et al.*, 2018). Modular plug-and-play continuous conveying systems are crucial to meet the increasing market requirements. Moreover, the introduced conveying systems should be supported by transfer trolleys, AGVs, AGVs transfer stations, and high-bay storage (Hofmann *et al.*, 2018). In this direction, Doh *et al.* (2016) discussed the application of automation technologies (e.g. self-guided vehicles, autonomous container handling systems, tracking systems, interactive agents) able to satisfy the new industrial demands of the so-called 4th industrial revolution.

Moreover, Modrak *et al.* (2019) reported on an expert survey where automatic control into delivery processes and the introduction of autonomous inventory management systems were rated as very important to change from the current to the expected Logistics 4.0 state.

Most of the literature discusses the necessity of modern information and communication technology (ICT) enabling smart supply chains, new process standardization, and organization models (Doh *et al.*, 2016; Kai *et al.*, 2017; Dallasega *et al.*, 2018; Gomes *et al.*, 2018; Chandriah and Raghavendra, 2019; Schniederjans *et al.*, 2020). Adaptive processes and supporting information systems are viewed as important Industry 4.0 technical innovations. To support these technologies and their interaction in a supply chain and logistics setting, standardized reference frameworks can provide great utility. Some of these studies propose reference architectures for specific technologies. This standardization includes the need for consensus protocols for Industry 4.0 – as this research is still in the early stages for supply chains.

A number of the identified studies – for example, Bhagawati *et al.* (2019) and Luthra *et al.* (2019) – have addressed sustainability aspects of logistics processes and how they relate to Industry 4.0 requirements. This literature suggests management should focus on IoT and environment-friendly practices to satisfy Industry 4.0 requirements.

Another series of related studies (Alias *et al.*, 2017; Furmann *et al.*, 2017; Burow *et al.*, 2018) investigated advanced planning and data analysis systems and their relationships to

Industry 4.0. These study foci were because one of the main Industry 4.0 visions is to improve how data in manufacturing are processed and integrated into the entire supply chain (Dallasega *et al.*, 2019). Relatedly, building on employee skills by supplying and analyzing operational data related to fostering operator's competences and know-how emerged as important (Seitz and Nyhuis, 2015). Other works support the need to have automated vehicles and logistic systems (Doh *et al.*, 2016; Hofmann *et al.*, 2018; Modrak *et al.*, 2019).

These Logistics 4.0 studies are primarily at a conceptual and theoretical level – which may contain logistics as part of their dimensions. For example, digitization enablers that can improve supply chain management have been proposed but without any statistical validation (Gupta *et al.*, 2020). This evidence confirms the fact that Logistics 4.0 is a relatively young research area, which necessitates greater development through empirical validation. While the conceptual literature informs scale item determination to measure Logistics 4.0, a multidimensional construct to measure Logistics 4.0 in manufacturing companies does not exist. It is useful to help make practical and research progress on this objective. Thus, we now employ an empirical methodology to help further this scale development.

3. Research methodology

This study aims at developing and validating an instrument to measure Logistics 4.0 to increase the understanding of the implementation of Industry 4.0 in the logistics processes of manufacturing companies. Considering the aspect of scale development in the field of logistics, various models have been proposed. Zhu *et al.* (2008) developed a scale measurement model for green supply chain management practices implementation among manufacturers. Rossiter Hofer and Knemeyer (2009) developed and validated a scale for controlling logistics complexity, while, similarly, Ojha and Gokhale (2009) developed and validated a scale for logistical business continuity planning in the field of supply chain risk management. In this direction, Li *et al.* (2009) developed a scale for measuring supply chain agility. Furthermore, Boon-itt *et al.* (2017) developed and validated a measurement scale to ascertain service supply chain management process capabilities.

Studies for scales to assess Industry 4.0 have focused on the development of maturity scales and assessment models (Samaranayake *et al.*, 2017; Ganzarain and Errasti, 2016; Trotta and Garengo, 2019; Caiado *et al.*, 2021). But these are not necessarily appropriate as scales for direct empirical evaluation; although they are useful for managerial purposes.

To develop and measure Logistics 4.0, we use a comprehensive, multi-step approach as suggested by several studies in the area of logistics and supply chain management (Churchill, 1979; Koufteros *et al.*, 1997; Nahm *et al.*, 2003; Shah and Ward, 2007). Figure 1 shows the research methodology and its detailed process steps.

The instrument development of the latent construct Logistics 4.0 is based on a review of related literature and subsequent focus group interviews. The preliminary construct of Logistics 4.0 consists of 16 items which are measured by using a 5-point Likert scale. After a pretest, data are collected on a broader basis from European, Asian, and USA respondents. This heterogeneous setting supports scale generalizability by including a multitude of differing cultural, organizational, and contextual characteristics (Zhu *et al.*, 2008). By conducting exploratory factor analysis (EFA), the validity and reliability of the Logistics 4.0 factors are tested. Moreover, we construct two models for further evaluation of Logistics 4.0 by using confirmatory factor analysis. Model 1 is operationalized as a first-order factor measurement model with covariances between the factors of Logistics 4.0 and model 2 is conceptualized as a second-order factor measurement model which defines Logistics 4.0 as a second-order construct.

3.1 Instrument development

In the first step, a literature review is used to achieve a better understanding of theory and recent measurement approaches regarding Logistics 4.0-relevant items based on the structured analysis of theoretical and conceptual studies. As discussed in section 2, the research team generated six categories for a pool of potential Logistics 4.0 items as a starting point for the subsequent qualitative analysis. In a second step, focus group interviews were conducted to incorporate expert input based on the guidelines of Tong *et al.* (2007) and Krueger and Casey (2015). In this context, the selection of key informants is seen as an important success factor that highly influences the validity of the research results (Kumar *et al.*, 1993). For the focus group interviews, we defined the key informants as specialists having clear and accessible knowledge in a specific field and, therefore, being responsible for the design, the implementation, and/or the control of a specific problem-solution and having exclusive access to crucial information (Mayer, 2002; Bogner *et al.*, 2005). Thereby, by using company directories, the research team approached logistics and supply chain managers who already practiced the implementation of Industry 4.0 technologies in logistics processes of manufacturing companies for the systematic gathering and evaluation of relevant statements. Table 1 provides an overview of the focus group interviews.

The research team conducted five focus group interviews with 37 participating enterprises and 67 participating experts.

The subsequent quantitative content analysis resulted in a total of 548 statements and 203 pure Logistics 4.0-related statements.

Before determining the final items for the scales, the literature review and 203 Logistics 4.0-related statements from the focus group interviews were clustered. The clusters and terms were re-evaluated by an independent expert team, consisting of eight academics and six professionals, to ensure the content and face validity of the measurement items (Zhu *et al.*, 2008). The proposed measurement model for Logistics 4.0 resulted in a preliminary set of 16 measurement items.

The underlying questionnaire to evaluate the measurement items was developed using recommended guidelines from literature (Moosbrugger and Kelava, 2012). Therefore, the items of the Logistics 4.0 measurement model were operationalized by using a 5-point Likert scale for Logistics 4.0 (1 = not important, 2 = slightly important, 3 = moderately important, 4 = important, 5 = very important). Likert scales are the most frequently used in modern empirical research because of their ease of use, a time-efficient conceptualization process, and their reliability (Bortz and Döring, 2007).

The resulting questionnaire was evaluated by experts from manufacturing companies and researchers from universities. Finally, the questionnaire was finalized with the feedback from the pilot tests with 36 enterprises by using an online survey. In addition, it must be stated that the execution of the empirical study was not influenced by the Covid-19 pandemic. Part 1 of the study, namely the focus group interviews, was conducted before the pandemic. Part 2, the survey, was conducted online, resulting in no Covid-19-related limitations.

	Northeastern-US	Central–Europe	Northern-Thailand	Total
Number of focus group interviews	1	3	1	5
Participating companies	10	17	10	37
Participants	16	26	25	67
Collected statements	140	310	98	548
Logistics 4.0-related statements	33	134	36	203

Table 1. Summary of the focus group interviews

3.2 Survey method and sample selection

The data collection for the proposed large-scale survey took place across three different continents. As outlined, we used this heterogeneous setting to ensure scale generalizability by including a multitude of differing cultural, organizational, and contextual characteristics in the final sample (Zhu *et al.*, 2008). In addition, we used a triangulated approach, where random sampling in the Northeastern-US and Central-EU, and theoretical sampling in Northern-Thailand were chosen. Theoretical sampling was used to decrease potential difficulties in obtaining relevant data, to avoid misunderstandings of the survey items by the target population, and to isolate potential confounding variables, while random sampling was chosen to compensate potential shortcomings in terms of validity and generalizability from the theoretical sampling approach (Zhu *et al.*, 2008).

In the first step, we contacted companies through randomized emails. Again, it is worth noticing that the approach for contacting the key informants is crucial for the validity of the research results (Kumar *et al.*, 1993). In the present case, the contact of the right information carrier was ensured by using professional membership directories. Therefore, the companies were identified by using a company directory from the ASCM (Association for Supply Chain Management) for the Northeastern-US and the ORBIS database for Central–Europe. Out of a total of 10,574 questionnaires (Northeastern-US 1,542, Central–Europe 9,032), 131 (Northeastern-US 59, Central–Europe 72) were completed, valid, and, therefore, useable for our research study. In the second step, we used theoretical sampling in Northern-Thailand. The guidelines for theoretical sampling approaches used were suggested by Eisenhardt (1989) and Patton (2002). A heterogeneous sample setting based on the number of employees, industry type, with a homogeneous setting in terms of geographical location (Northern-Thailand) was used to isolate potential biases (Saunders *et al.*, 2003). We directly contacted respondents by explaining the purpose of the study and face-to-face collection of questionnaires. As an incentive to participate, respondents were provided with the results in the form of a report and a presentation. In addition, participants will receive further studies in the form of a newsletter on request. In sum, the theoretical sampling approach resulted in 108 valid and, therefore, useable answers.

Overall, the final sample was comprised of a total of 239 responses. In this regard, the statistical power and precision of a CFA (and SEM in general) model parameter estimates are influenced by the sample size (Brown, 2015). A sample size of >200 participants offers adequate statistical power for data analysis (Hoe, 2008; Singh *et al.*, 2016). This suggestion is also in line with the recommendations of Comrey (1988) who proposes >200 participants as generally adequate for a measure having up to 40 items. This parameter is met by the present sample ($N = 239$). Moreover, a t-Test did not show any noteworthy significant differences (p-Value <0.05) between the random sampling and the theoretical sampling approach. Moreover, non-response bias was tested using the recommendations from Armstrong and Overton (1997) comparing early versus later respondents. The group comparison test did not show any significant differences between the earlier and later respondents. This higher degree of homogeneity in the sample further enhances the transferability and the representability of our research results (Bortz and Döring, 2007; Hair *et al.*, 2019). Furthermore, an analysis of variance (ANOVA) showed no significant differences in the indicators between the Northeastern-US, Central-EU, and Northern-Thailand respondents. Despite the heterogeneous setting of the individual countries, which is reflected for example in different cultural, organizational, and contextual characteristics, the generalizability of the developed scale can be further substantiated (Zhu *et al.*, 2008).

In addition, we controlled for a common method bias by using multiple key informants and through the standardized study procedures. Moreover, from a statistical point of view, the single-method factor procedures did not indicate a common method bias (Elbanna and Child, 2007; Ellis *et al.*, 2010; Jakobsen and Jensen, 2014 Kaufmann *et al.*, 2014).

Considering the number of employees, 54.6% of respondents are from enterprises with 0–100 employees, 9.7% from enterprises with 100–250 employees, and 12.2% from enterprises with 250–500 employees. The remaining 23.5% are from enterprises with more than 500 employees.

Respondents are mainly from the metal industry (39.6%), followed by the retail/food/clothing industry (37.8%). The remaining respondents are from finance/consulting/education (9.6%), electronics (6.5%), paper/wood (3.9%) and chemicals (2.6%).

Job descriptions included 38.4% CEO/owners of the companies, 34.5% logistics or SCM managers, and 27.1% employees working in a logistics-related position.

The detailed description of the third step of our research methodology - data analysis in Figure 1 - is included in Sections 4.1, 4.2, and 4.3.

4. Results

4.1 Descriptive analysis: Descriptive statistics of the preliminary scale items to assess Logistics 4.0

Based on the literature review and various focus group interviews, a list of 16 items of Logistics 4.0 for manufacturing enterprises was defined. Table 2 summarizes the final Logistics 4.0 items validated through the international survey. In the first step, the survey results were analyzed using basic statistical notions.

All items were rated with a mean value greater than 3.74 on a scale of 1–5. Considering the variability of the survey results, the standard deviation ranges from 0.838 to 0.916. These requirements were rated as important for Logistics 4.0 and respondents were relatively consistent in their evaluations.

4.2 Explorative factor analysis: validity and reliability testing

As an initial step, we conducted an EFA with principal axis factoring as the extraction method and ProMax with Kaiser normalization as rotation method, leading to three factors, respectively constructs, established by six iterations. Seven of the preliminary 16 items are removed due to low factor loadings, leaving a total of nine items and three factors for the final Logistics 4.0 measurement model.

The EFA further resulted in 0.92 for the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy which shows the appropriateness of the factor analysis and an approximate Chi-Square of 2,107.065, df 120 with p-Value < 0.05 for the Bartlett's test of sphericity resulting in no issues in inter-matrix correlations (Hair *et al.*, 2019). Table 3 displays the factor loadings.

We use confirmatory factor analysis (CFA) to determine the validity and reliability of the scales; this evaluation is based on Fornell and Larcker (1981). The results are displayed in Table 4.

For reliability, Cronbach's alpha (CBA) values for all the three factors (factor 1: CBA = 0.866, factor 2: CBA = 0.795, factor 3: CBA = 0.888) are above the threshold of 0.70. For convergent validity, composite reliability (CR) for the three factors (factor 1: CR = 0.796, factor 2: CR = 0.870, factor 3: CR = 0.893) should exceed 0.70 and the average variance extracted (AVE) for the three factors (factor 1: AVE = 0.565, factor 2: AVE = 0.691, factor 3: AVE = 0.737) should be higher than 0.50. These results are true for all three factors. For discriminant validity the average variance extracted (AVE) should be higher than the maximum shared variance (MSV) and the AVE of the factor should be higher than the squared correlation between the factor and all other factors. AVE > MSV and the AVE of a latent variable should be higher than the squared correlations between the latent variable and all other variables. These results are true for all three factors (Hair *et al.*, 2019). In sum, all tests provide evidence for the validity and reliability of our Logistics 4.0 construct.

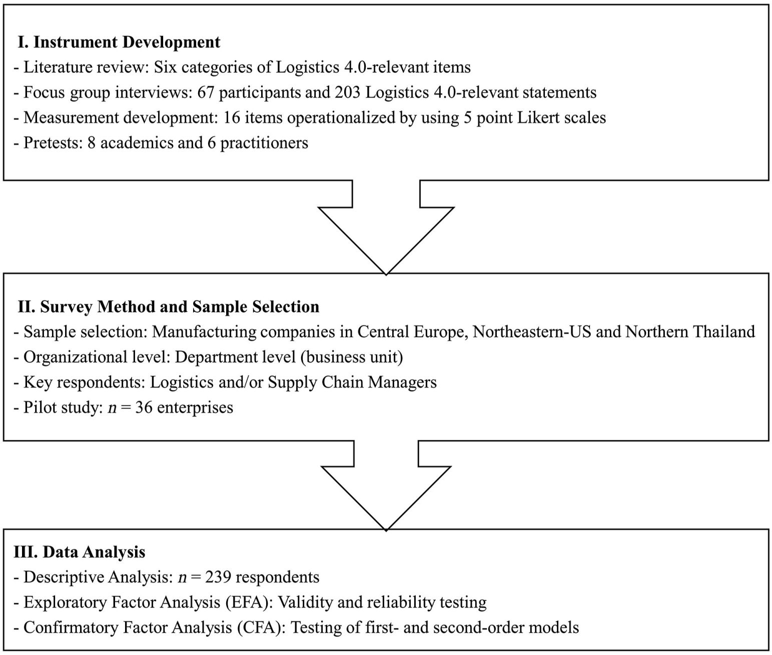

Figure 1.
The research process for scale development

4.3 Confirmatory factor analysis: testing first-order and second-order models

In the previous section we identified three factors for the Logistics 4.0 measurement model; factor 1 (item 6, item 7, item 12), factor 2 (item 3, item 8, item 10), and factor 3 (item 13, item 14, item 15).

We first determined whether a first-order measurement model exists. A first-order model for Logistics 4.0 implies that the three factors are correlated and are, therefore, dependent on each other and can be used to evaluate the complete construct without an intermediary latent factor. The covariance-based model resulted in acceptable support with 0.59 between factor 1 and factor 2, 0.61 between factor 2 and factor 3, and 0.62 between factor 1 and factor 3.

A second-order model implies that the three factors form the higher-order factor Logistics 4.0 (Log 4.0). The model resulted in acceptable factor loadings (>0.70), namely 0.76 for factor 1, 0.77 for factor 2, and 0.80 for factor 3 (Hair *et al.*, 2019). Both CFA model results are displayed in Figures 2 and 3.

Various goodness of fit indices for both models show identical results for model 1 and model 2. The models result in the following values: CMIN = 42.361, df = 24, CMIN/df = 1.77, GFI = 0.962, CFI = 0.985, NFI = 0.966, RMSEA = 0.57; PCLOSE = 0.320. However, all computed parameters showed values above the recommended thresholds as suggested by Hu and Bentler (1999). Therefore, model 1 and model 2 can be considered reliable and valid. In sum, Logistics 4.0 (Log 4.0) can be conceptualized as a first-order measurement modeland as a second-order measurement model consisting of three factors.

5. Discussion

In this section, we discuss how the results may be used and evaluated. Initially, an analysis of how model items and factors relate to the literature is presented. Next, based on the

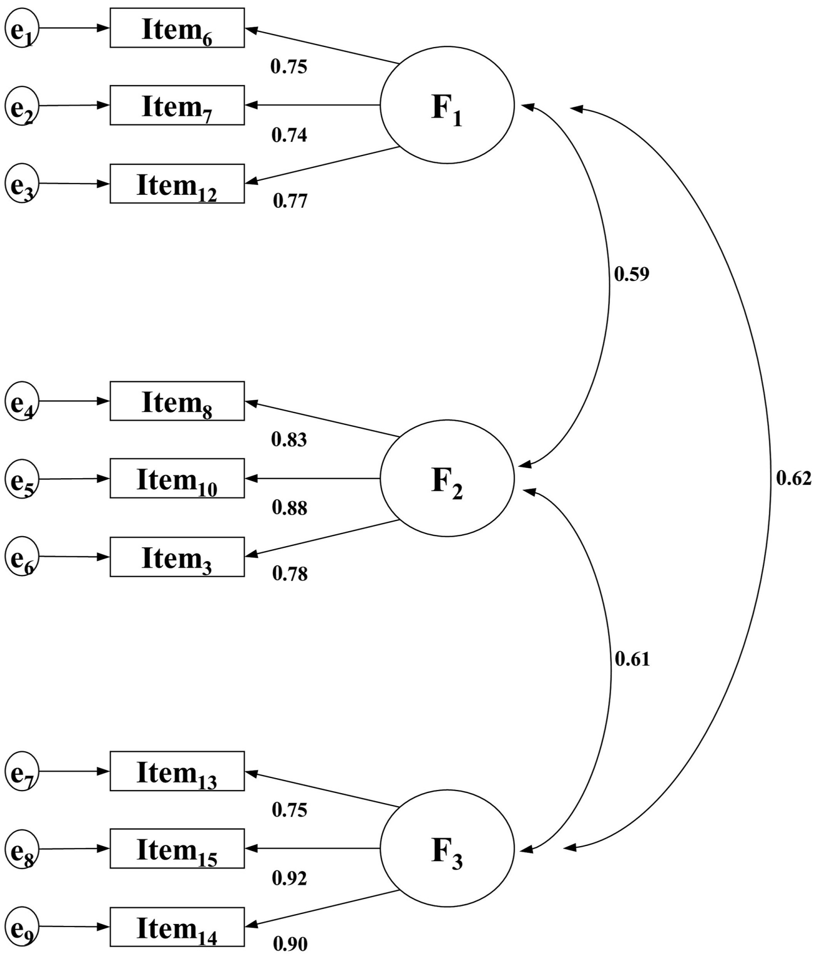

Figure 2.
First-order model (detailed model fit values: CMIN = 42.361, df = 24, CMIN/df = 1.77, GFI = 0.962, CFI = 0.985, NFI = 0.966, RMSEA = 0.57; PCLOSE = 0.320)

discussion of the Logistics 4.0 measurement model, the contribution to knowledge is described. We then discuss the practical and managerial implications of these scales and measurement items. Research and theoretical implications and directions for future research complete this section.

5.1 Logistics 4.0 measurement model

Figure 4 shows the proposed model to measure Logistics 4.0. It encompasses three factors, each entailing three items.

The items "*Advanced Planning and Control Systems for Rapid Demand Changes (item 6)*", "*Employee Training for Data Analysis (item 7)*" as well as "*Work Instructions for Supply Chain Collaboration (item 12)*" can form a factor we have named "*Building Organizational Capacities*". Markets are becoming more volatile (Spath *et al.*, 2013), and increased customization of products and services requires that companies respond quickly to address customer demand (Kai *et al.*, 2017; Evtodieva *et al.*, 2019). Emergent technologies

Table 2.
List of validated items of Logistics 4.0 for manufacturing enterprises (1 = not important, 2 = slightly important, 3 = moderately important, 4 = important, 5 = very important)

Item	Items of Logistics 4.0	*N*	Mean	Std. dev.
1	The assurance of data security throughout the supply chain	239	4.289	0.872
2	The availability of real-time order information regarding the status of production and shipping throughout the supply chain	239	4.280	0.841
3	The transparency of inventory levels and storage locations throughout the supply chain	239	4.276	0.850
4	The on-demand (Just-in-Time) production and delivery of products to the customers	239	4.213	0.855
5	The identification and avoidance of material flow breaks throughout the supply chain	239	4.163	0.866
6	Advanced planning and control systems for rapid demand changes	239	4.021	0.914
7	Training employees on state-of-the-art software and data analysis tools	239	4.017	0.860
8	The digital connection of customers and suppliers for an improved collaboration throughout the supply chain	239	4.017	0.865
9	The alignment of ERP/database systems throughout the supply chain	239	4.013	0.862
10	The digital tracking of products throughout the supply chain	239	4.000	0.879
11	The usage of decision support systems for planning and controlling of logistics (e.g. for supplier selection decisions)	239	3.971	0.881
12	Work instructions for collaboration throughout the supply chain by using information and communication technology	239	3.845	0.838
13	The usage of automated ordering systems	239	3.808	0.891
14	The self-control of warehousing processes (autonomous processes)	239	3.778	0.887
15	The self-control of material flow processes (autonomous processes)	239	3.766	0.891
16	The limitation of data accessibility to different stakeholders in the supply chain	239	3.736	0.894

Table 3.
Factor loadings (pattern matrix)

	Factor 1	Factor 2	Factor 3
Item 6	0.721	0.037	−0.009
Item 7	0.666	−0.011	0.071
Item 12	0.843	−0.196	0.109
Item 8	−0.085	0.821	0.100
Item 10	−0.172	0.944	0.054
Item 3	0.019	0.746	0.053
Item 13	−0.034	0.21	0.633
Item 15	0.049	0.008	0.879
Item 14	0.052	−0.058	0.916

Table 4.
Validity and reliability criteria

CBA, CR, AVE, MSV values					Factor correlations			
	CBA	CR	AVE	MSV		Factor 1	Factor 2	Factor 3
Factor 1	0.866	0.796	0.565	0.373	Factor 1	0.752		
Factor 2	0.795	0.870	0.691	0.381	Factor 2	0.586	0.831	
Factor 3	0.888	0.893	0.737	0.381	Factor 3	0.611	0.617	0.859

such as big data analytics, deep learning algorithms, machine learning, and IoT could support decision-making in this field (Evtodieva *et al.*, 2019).

Adoption of new technologies requires new employee competencies and capacities to supply and analyze operational data (Seitz and Nyhuis, 2015). In addition to new technology

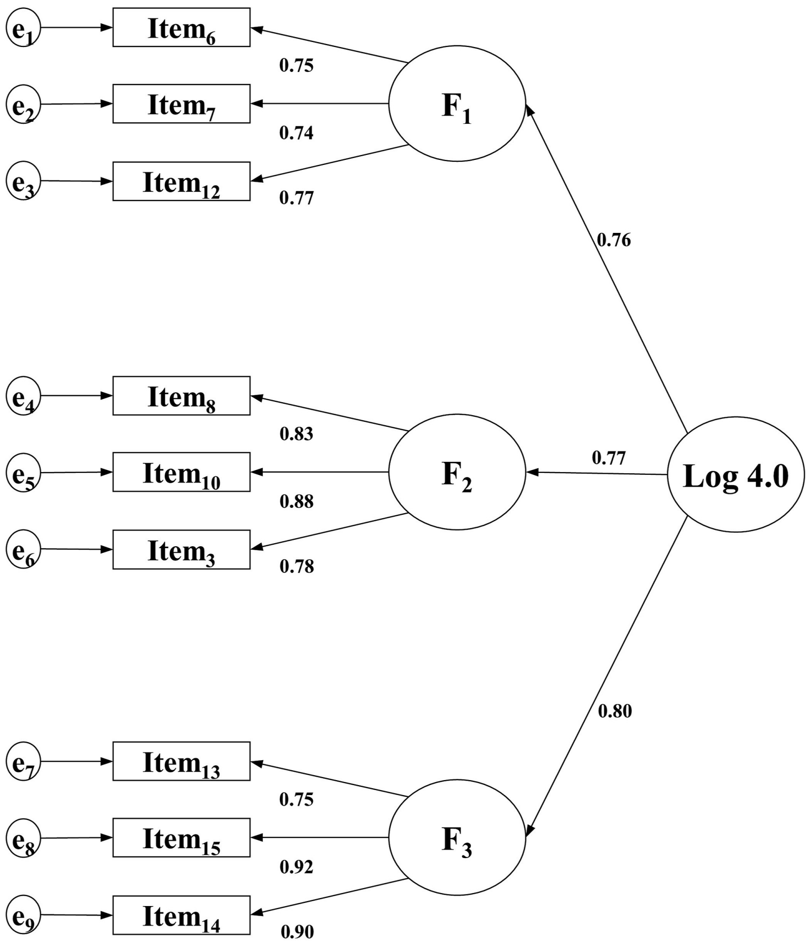

Figure 3.
Second-order model (detailed model fit values: CMIN = 42.361, df = 24, CMIN/df = 1.77, GFI = 0.962, CFI = 0.985, NFI = 0.966, RMSEA = 0.57; PCLOSE = 0.320)

usage, employee training for managing these technologies – such as advanced data analysis – is required. To support and guide an effective collaboration between different actors over the supply chain, worker training and instruction in processes, procedures, and policies are needed to build a stronger logistics channel. Each of these activities can be complementary in that collaborations can also be supported through analytics and technological capacity building of workers.

The items "*Customer Supplier Connection in the Supply Chain (item 8)*", "*Product Tracking Supply Chain (item 10)*" and "*Inventory Transparency in the Supply Chain (item 3)*" are items that fit within the second factor entitled *"Interconnection and Material Flow Transparency"*. A main contribution of the fourth industrial revolution is how manufacturing data are integrated over the whole supply chain (Burow *et al.*, 2018; Dallasega *et al.*, 2018; Gomes *et al.*, 2018). The synchronization of data should be extended over the boundaries of a company by connecting customers and suppliers within the supply chain. This characteristic is a basic requirement to quickly sense demand variations in terms of changing and prioritizing orders

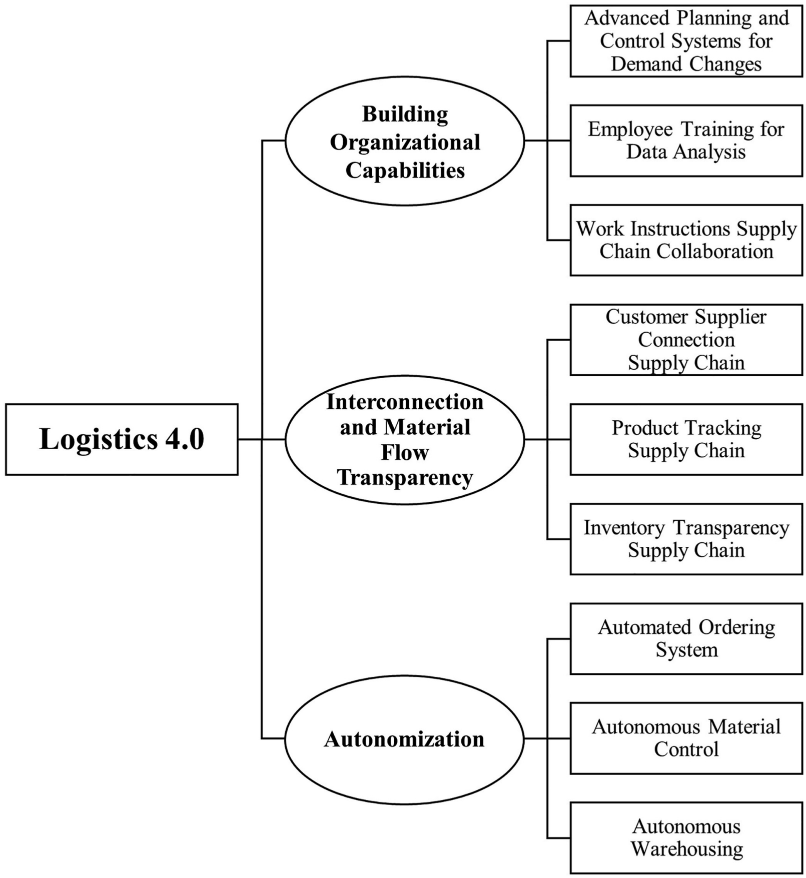

Figure 4.
Logistics 4.0 measurement model

in real-time (Dallasega *et al.*, 2019). Continuous product tracking over the supply chain can improve productivity.

Logistics 4.0 systems should provide real-time information on the location and status of manufactured items – semi-finished as well as finished products – as they flow through the supply chain (Ramadan *et al.*, 2017). This information facilitates supply chain planning and controls limiting waste from overproduction, excessive inventory, waiting and search time (Rauch *et al.*, 2018).

According to Valente and Neto (2017), RFID in combination with IoT technologies are the main enablers for product tracking systems. Inventory should be tracked and managed throughout the supply chain for full inventory transparency. Intelligent warehouse management systems can accomplish some of these tracking and management activities to prevent out-of-stock situations, lower capital investment levels, shorter lead-times, and an enhanced management decision capability to improve customer service levels (Barreto *et al.*, 2017).

The items "*Automated Ordering System (item 13)*", "*Autonomous Material Control (item 15)*", and *"Autonomous Warehousing (item 14)"* are items that form the third factor entitled *"Autonomization"*. Industry 4.0 technologies such as Additive Manufacturing (AM) allow a direct – out of computer-aided design data – and autonomous manufacturing of highly customized parts. The ordering process in this environment still requires substantial manual effort; this process includes order acceptance, assessment of manufacturability, and offer calculation (Rudolph and Emmelmann, 2017a). To transition from manual activities, Automated Ordering Systems become increasingly important to support the process of order acquisition, assessment and processing (Rudolph and Emmelmann, 2017b).

Rising labor costs and skilled labor shortages foster the introduction of autonomous material control systems. Systems include mobile robots, driverless forklifts, unmanned aerial vehicles, modular changeable plug-and-play conveying systems (Hofmann *et al.*, 2018), autonomous transfer trolleys, and container handling systems (Doh *et al.*, 2016). In addition to efficiency improvements, improved safety from separating human activity from large vehicle traffic occurs. Electronic commerce has raised customers' expectations for faster and cheaper deliveries; these expectations require warehouses to be more automated (Modrak *et al.*, 2019).

The following section discusses with theory the items that were not included in the Logistics 4.0 measurement model. Concepts like on-demand production, Just-in-Time production and delivery (Item 4) as well as the identification and avoidance of material flow breaks (Item 5) are the main principles of the Lean and Agile Management approaches (Golhar and Stamm, 1991). Thus, respondents may not have assigned them consistent importance levels in the field of Logistics 4.0. According to the survey results, the usage of decision support systems for planning and controlling of logistics (Item 11) was not attached to consistent importance. This can be explained because the potential of advanced decision support systems using industrial big data analytics and machine learning algorithms, is not well known in the industry especially because of a lack of skilled personnel (Rogers and Kalinova, 2021; Kumar *et al.*, 2021). Similarly, also the limitation of data accessibility to different stakeholders (item 16) and the assurance of data security throughout the supply chain were not rated consistently as important (Item 1). This contrasts with recent research that investigates the capability of blockchain-based systems mitigating problems of security threats and privacy leak risks during the operation phase of intelligent logistics systems (Fu and Zhu, 2019; Li *et al.*, 2021).

Overall, Logistics 4.0 practices are multidimensional and not limited to specific practices requiring a more nuanced and holistic definition, scales and metrics. Thus, our proposed Logistics 4.0 measurement model combines the leveraging of increased organizational capabilities with the rise of interconnection and material flow transparency and the setting up of autonomization in logistics processes.

5.2 Contribution to knowledge

Logistics 4.0 is a relatively young research area, which necessitates greater development through empirical validation. Many different conceptual elements, technologies and enablers of Logistics 4.0 are proposed in the literature (Burow *et al.*, 2018; Evtodieva *et al.*, 2019; Winkelhaus and Grosse, 2020). However, most studies are still relatively conceptual and theoretical. Some basic constructs of Logistics 4.0 exist but empirically validated measurement items and scales are currently missing. This is also underpinned by recent literature (Bag *et al.*, 2020; Winkelhaus and Grosse, 2020).

Therefore, our paper proposes a Logistics 4.0 measurement model that was developed and validated by using an exploratory and confirmatory factor analysis and a large-scale survey. While technological advancements are still important, our research also includes a human-centric view. This is highlighted by mentioning that employee training for data analysis is important to increase operators' capabilities to appropriately read and interpret the flood of data generated by logistics equipment. Furthermore, cognitive assistance systems to identify and consider rapidly demand changes as well as to provide work instructions for collaboration throughout the supply chain emerged as very important for the future logistics operators. In addition, it came out that autonomization is also important for logistics processes and not only for production systems. The cognitive workload of human operators will increase in future factories (Rauch *et al.*, 2020), thus systems that provide an automated ordering, an autonomous material control as well as a self-control of warehousing processes will give great support. The proposed Logistics 4.0 measurement model can even be a basis for newer logistic-related research (Østergaard, 2018; Paschek *et al.*, 2019; Bag *et al.*, 2020) including end-user demand and last-mile logistics within Industry 4.0's autonomization and supply chain-wide demand, materials, and inventory communication.

5.3 Managerial implications

Practitioners can use the proposed measurement model in a variety of ways. They can assess their current level of readiness and maturity for the implementation of various practices. For example, a customer-supplier connection maturity level may include "not implemented", "implemented at a limited level" (only with critical dimensions adopted), "implemented at a good level" (most are connected), and "fully implemented".

Practitioners can map the current state and derive appropriate implementation plans for a short-, medium- and long-term perspective. They can benchmark against best practices across or between industries on these metrics. The conceptualization of the construct at higher levels, (first- and second-order), allows practitioners to observe Logistics 4.0 practices implementation at a higher level – and easy to understand single dimension – that easily aggregates individual items. A complete package will require all items for a full-fledged adoption of Logistics 4.0. If an item underperforms it cannot be compensated with the adoption of another one – the items are not necessarily interchangeable or separable. As a practical example, factory or warehouse automation should go together with the interconnection of material flow processes over the supply chain to reach the capability of Logistics 4.0. However, by using the scale in cause-effect investigations, it is important to notice that a lack of correlation between the Logistics 4.0 measurement model and a set of performance indicators should not be interpreted as a failing of the scale.

Moreover, the metrics can also evaluate supply chains and supply chain partners for their capabilities to function effectively in a Logistics 4.0 environment. The strengths and weaknesses of partners need to be known since many of these technologies and practices are inter-organizational. Thus, not only can the metrics be used for individual organizations but can be evaluated across a network. It may not be every participant in the supply chain that would need to be evaluated – this is an infeasible and difficult proposition – only critical partners or supply chain links are likely necessary for effective broad-based supply chain Logistics 4.0 capabilities.

5.4 Research implications and limitations

The research implications for this work are relevant to the pursuit and advancement of research on the topic of Logistics 4.0. The lack of scale items and consensus definitions in this field – a cognitive dissensus – currently exists. Although these are technological terms, much of the empirical research can be rightfully positioned as social sciences in the adoption of practices in organizations. Without the appropriate measurements and indicators, theory and academic investigation cannot be advanced (Salisbury *et al.*, 2002). This step is an important one and we feel that theoretically sound scales will be important for this emergent integrative technology.

The scales are valuable to identify linkages to important research questions that are currently investigated and emerging. For example, antecedents to adoption can be linked to these scales, as well as determine the Logistics 4.0 practices related to performance. Theoretical constructs and theories related to technology management and adoption such as diffusion of technology (Geroski, 2000) or technology acceptance (Lee *et al.*, 2003) or organizational theory such as institutional and/or resource-based theory (Zhang and Dahliwal, 2009; Reischauer, 2018) can be furthered. As an example, antecedents from institutional pressures, mimetic and normative pressures, may induce companies to have varying levels of Logistics 4.0 practices. Scales for pressures exist, and these new scales for Logistics 4.0 pressures can be linked to the institutional pressures. This allowance and expansion of new and existing theory to this field is currently a major gap in the research for these emergent technologies.

Supply chain management research can also benefit given the logistics aspects of these scales. For example, important research questions such as – Do supply chains with greater evidence of Logistics 4.0 characteristics across partners perform better than supply chains with lesser Logistics 4.0 characteristics? Clearly, many such questions can be answered.

These scales represent dimensions and factors for a significant research stream that utilizes formal analytical prescriptive models. These models serve multiple purposes including, but not limited to, evaluating best practices, selection of partners, to optimization of organizational operational activities. For example, evaluation and selection of technologies and alternatives for organizations is one such direction. The dimensions may be utilized for multiple criteria decision-making when selecting technologies or projects for organizations to help them compete on Logistics 4.0 dimensions. Supplier selection models are also very popular, and these scales may be utilized to determine which suppliers to select to help them achieve the goals associated with Logistics 4.0 metrics.

These are only some examples of how theoretical scales can be utilized in research. The logistics, operations and supply chain academic communities are obvious beneficiaries of those tools. Technology and engineering management, general management, policy, and even sustainable development fields (Bai *et al.*, 2020) and scholarly communities can also benefit.

Although the scales developed in this research have significant utility, we must identify a few caveats and limitations that can set the stage for future research. In our paper, additional contextual factors have not been investigated. In the present study, 64.3% of the participating companies had a headcount of fewer than 250 employees. Although an initial Kruskal-Wallis-Test mostly did not reveal significant differences in the indicators of our Logistics 4.0 measurement model (p-Value<0.05), detailed investigations should be carried out in subsequent studies. In this regard, the digital connection of the whole supply chain may be more important for a larger organization than for a small and medium-sized enterprise (SME). We did not decipher these potential differences and the scales would need to be tested in each situation. For example, the utility of certain dimensions and their inclusion for large companies – who have greater capability and need to manage the whole supply chain – may be dissimilar to smaller manufacturing enterprises. Industrial differences may also exist for certain items. As a practical example, the continuous tracking of products over the supply chain may be more important for food industries. This could be explained by the necessity to guarantee an uninterrupted refrigeration chain due to the expiration dates of food products. Whether these scales hold for specific types of industries or are truly generalizable across industries will require further investigation as well.

Furthermore, the importance of the order in which companies should implement the three factors of Logistics 4.0 has not been investigated in this research. As a practical example, specific employee training may be needed to successfully increase the automation degree of logistics processes through advanced IT technologies and autonomous material handling systems. This should be investigated in detail in future research activities.

As a further need for research, the items for Logistics 4.0 should be validated by interrelating them with specific performance measures. As a practical example, high transparency of inventory over the supply chain may lead to low capital costs due to the avoidance of unnecessary levels of stock. Here, the study can be used as basis to collaborate with operations consultancy companies to both apply the scale and generate empirical data for follow-on studies and further validation. These investigations are important and necessary also for further theoretical validation of the measures.

6. Conclusion

The implementation of Industry 4.0 technologies and concepts plays a significant role in developing sustainable competitive advantages for industrial enterprises and their supply chains. This study introduces a new measurement model for the evaluation of Logistics 4.0 in manufacturing companies – and their supply chains. The development process included a systematic literature review, focus group interviews, and an international survey. The result is a psychometrically sound, validated, and reliable 9-item measurement scale. The identified measurement items are crucial attributes for the successful implementation of Logistics 4.0; but also for the theoretical advancement of this field.

Little attention has been paid to an instrumentalization of Logistics 4.0 in logistics, supply chain, or operational research. The developed scale opens various possibilities for future research and practical applications. It can be used to measure Logistics 4.0 by itself and it can be utilized to investigate the causal relationships between the Logistics 4.0 concept and related operational and financial performance measures. It can also be integrated with various theoretical constructs and situations from across multiple disciplinary fields.

The validated scale items increase the understanding of the management of Logistics 4.0 in manufacturing companies. The factors and their underlying items can be used to develop strategies, which decrease barriers and threats within the implementation phase.

As a limitation, the study can only be generalized within the scope of our pre-defined sample. Therefore, we suggest a subsequent evaluation and refinement of the scale by using samples from a different population. Moreover, scales should be further validated by using structural equation modeling which should investigate interdependencies between Logistics 4.0 and a set of independent variables; which can and should be grounded in strong theoretical foundations.

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