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Dependency on core and emerging technologies of Logistics 4.0 in freight transport enterprises' management

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ABSTRACT

The crucial purpose of the paper is to present the outcomes of the analysis concerning the effects of technological solutions of Logistics 4.0 on logistics resources and customer service in freight transport enterprises. The paper identifies four core and seven emergent technologies of Logistics 4.0 as catalysts for the enhancement of logistics customer service in the freight transport sector. Empirical data were acquired from 460 freight transport enterprises located in Poland through the application of a survey methodology. Within the adopted research framework, confirmatory factor analysis was conducted initially, followed by the application of structural equation modelling using the partial least squares (SEM-PLS) approach, with a post hoc analysis subsequently performed to identify patterns of similarity in the observed effects. It has been demonstrated that both core and emerging technologies of Logistics 4.0 within freight transport enterprises constitute valuable instruments facilitating access to critical information relevant to logistics customer service. Simultaneously, findings suggest that emerging technologies of Logistics 4.0 in service-related benefits are conditional, temporally delayed, and strongly dependent on implementation depth, organisational readiness, and systemic integration. Additionally, the analysis revealed that logistics resources serve as a mediating variable in the relationship between both core and emerging Logistics 4.0 technologies and logistics customer service.

Keywords: Logistics 4.0, logistics customer service, logistics resources, freight transport enterprise, management.

INTRODUCTION

The digital transformation within freight transport constitutes a fundamental pillar of Logistics 4.0, emerging as a direct consequence of the fourth industrial revolution (Industry 4.0) [1, 2]. The advent of Logistics 4.0 introduces a new array of challenges for logistics operations, particularly for freight transport enterprises, which are now compelled to enhance managerial efficiency and operational effectiveness through the integration of Industry 4.0 technologies and conceptual innovations into logistics processes [3, 4]. As noted by Barreto et al. [5], Logistics 4.0 constitutes a paradigmatic shift toward fully digitised and interconnected logistics systems, underpinned by cyber-physical infrastructures and the deployment of advanced digital technologies. The onset of Logistics 4.0 [6, 7] poses significant challenges to the contemporary freight transport sector, while simultaneously offering unprecedented opportunities to harness disruptive technologies for the development of novel business models. As discussed by Chen et al. [8], and Modica et al. [9], they are in parallel with the enhancement of existing operational paradigms. This transformative momentum has stimulated growing interest among diverse stakeholder groups in comprehending the nature and implications of core and emerging, disruptive technologies in the context of road freight transport [10, 11]. Furthermore, this evolution serves as a catalyst for logistics resources in logistics management, as evidenced by the research of Tubis and

Grzybowska [12], with the overarching aim of identifying and actively leveraging opportunities arising within the external environment and fostering the development of innovative solutions, according to Wojewódzka-Król [13].

Simultaneously, changes in logistics technology in recent years undeniably influence buyer-seller interrelations and their consequences on customer service, also in road freight transport companies. As reported in digital business survey [14] in the evidence of the investigation conducted among over 700 managers of the companies, for nearly half of the research group, the designated area of developing customer service is digital technology solutions. From an opposite perspective, such as opinions of professionals in digital technological offers, presented by Altimeter-Prophet Research Group [15], the findings seem to be analogous owing to the indication that for over half of the respondents, the leading attempts are focused on enhancing the form of contact with customers. It is confirmed to a certain extent by the results achieved by Econsultancy Research Agency [16], which refer mainly to the 58% of the scrutiny group who chose customer orientation as the most imperative attribute for prosperity in the digital economy. Moreover, Accenture Digital [17] achieved in the results of common research definited endorsement that for 40% of respondents the level of customer service increases if digital technology is used. A higher level of customer service is correlated with customer loyalty, while according to Coleman [18] research, the activities, methods or tools which if adequate practiced to enhance customer loyalty help to improve the enterprise's profitability by more than 25%. In the transport sector, as presented by PricewaterhouseCoopers [19] survey findings, more than 11% of top managers of the companies estimated that implementing digital technology solutions may increase the level of customer service, and for 16% of executives, these technological investments may increase profit. Ultimately, in the era marked by heightened customer impetuosity, core and emerging technological solutions of Logistics 4.0 seem to be inherent to acquire the entire perceptibility of customers' requirements and needs [20].

Grounded in theoretical postulates, some contributions in the literature, i.e. by Kamasak [21], support the conceptualisation of logistics customer service as a strategically embedded organisational resource, integral to the attainment of durable competitive superiority. Building upon this foundation within the framework of the resource-advantage paradigm and the theory of competition, both technological innovations and essential customer-related informational structures are posited as intrinsic and structurally embedded components of firms' strategic architectures [22]. Resources yield competitive asymmetries by equipping firms with the operative capacities to design and deliver services which, relative to those of market rivals, are either distinctly perceived by customers as augmenting value or are configured to incur comparatively diminished transactional costs. From the analytical standpoint presented by Chen and Perez [23], and Purwoko et al. [24], logistics customer service encapsulates the extent to which logistics capabilities are mobilised and integrated in pursuit of competitive predominance. The enterprise's preferential market position emerges predominantly from the service components strategically interfaced with the core product offering. Moreover, customer-centric orientation and reciprocal engagement are identified as critical axioms within the resource-based theoretical framework, which has been extensively examined and validated as an analytically robust construct for the strategic orchestration of information technology investments [25].

In light of the aforementioned concisely outlined implications, the purpose of this paper is to present the outcomes of the analysis regarding the impact of technological solutions of Logistics 4.0 on logistics resources and logistics customer service in freight transport enterprises. The paper identifies four core and seven emergent technologies of Logistics 4.0 as catalysts for the enhancement of logistics customer service in the freight transport sector. A critical analysis of the literature on the subject, the most significant results of which are presented in the following section of the article, confirmed the absence of prior empirical evidence on the proposed interrelation between the specified objectives, thus indicating a clearly defined research gap within these domains of logistics management. As noted by Daugherty et al. [26], logistics customer service can be conceptualised as a multidimensional construct composed of distinct elements, characterised by diverse approaches, and subject to influence from a wide array of variables. By adopting this perspective on the comprehensive nature of logistics customer service, the present study endeavours to conceptualise it as a dynamic construct inherently interconnected with the technologies of Logistics 4.0, while concurrently being conditioned by the aforementioned logistics resources.

LITERATURE REVIEW

Core and emerging technologies of logistics 4.0

The contemporary discourse concerning Logistics 4.0 predominantly underscores the nascent stage of the concept, as it tends to focus primarily on theoretical and conceptual frameworks [27]. The Logistics 4.0 paradigm appears to reflect an integrated, digital system for managing the flows of materials, information, and energy, leveraging Industry 4.0 technologies with the objective of establishing intelligent and adaptive supply chains [28]. Nowicka [29] defines Logistics 4.0 as a process of digital transformation within logistics, aimed at enhancing transparency, automation, and efficiency across the entire value chain. According to Glistau [6], Logistics 4.0 constitutes a logistics system capable of sustainably satisfying individualised customer demands without incurring additional costs, supporting advancements in industry and commerce through the application of digital technologies. Furthermore, Barreto [5] articulates the Logistics 4.0 paradigm as the optimisation of both inbound and outbound logistics processes, enabled by intelligent systems embedded within software and databases that disseminate relevant information, thereby facilitating a high degree of automation. As summarised by Sun et al. [30], the overarching aim of this concept is to augment flexibility, transparency, and operational performance throughout the supply chain by fostering real-time data exchange, autonomous decision-making, and seamless integration between physical and digital processes.

This transformative conceptualisation of Logistics 4.0 incorporates technologies whose recognition is essential for its conceptual delineation, although the literature offers numerous insightful contributions aimed at defining the term "technology". Several classification frameworks have also been proposed, encompassing definitions that conceptualise technology as a utilitarian instrument, a mechanism denoting intentionality, a form of enhancement, or a heterogeneous construct embedded within human contexts. In the interpretation offered by Volti [31], technology is understood as a system devised by humans that employs knowledge and organisational practices to produce artefacts, methodologies, and capacities in pursuit of specific objectives. In this foundational sense, technology encompasses both the artefacts themselves and the processes by which they are developed [32].

Within the literature on the hierarchy and systematisation of technologies, numerous typological frameworks have been proposed. One of the more widely recognised classifications, advanced among others by Little [33], distinguishes between basic, core, and emerging technologies, terminology that is also employed by Takala et al. [34] as basic, core, and spearhead technologies. In consideration of the aforementioned characteristics of Logistics 4.0, technologies classified as basic are typically excluded from its advanced scope, given their conventional nature and widespread use in prior technological phases. Instead, emphasis is placed on core technologies, understood as the currently competitive technological assets of an enterprise, those of strategic significance for sustaining competitive advantage, the mastery of which is essential for acquiring the competencies required to succeed within the sector [35]. Additionally, emerging technologies are to be considered; these are future-oriented, still under development, and characterised by limited contemporary application, yet possessing substantial transformative potential [33].

In light of the conducted review of sources concerning technological solutions of Logistics 4.0 in freight transport enterprises, the available research does not explicitly address the classification of technologies into core and emerging categories. At the same time, numerous scholarly contributions report the results of empirical research that implicitly apply such a distinction by identifying currently implemented and competitive Logistics 4.0 technologies within transport enterprises, as well as technologies that are expected to constitute the operational and managerial backbone of these organisations in the near or more distant future. In consideration of the space limitations of the present article, the results of the conducted review of sources within this thematic scope are not discussed in detail; instead, attention is directed to the most salient conclusions, presented below.

The prevailing majority of researchers examining technologies in the era of Logistics 4.0 share the view that a process of digital transformation within the freight transport sector is already underway and is expected to intensify over the next decade. This transformation is anticipated to contribute to revenue growth among transport enterprises, as well as to improvements in service quality delivered to customers. In line with empirical insights reported, inter alia, by the Polish Road Transport Institute [36], PwC [37], TLP [38], and Trans.Eu [39], the freight transport sector is characterised by substantial untapped potential for development through digitalisation, encompassing both internal and external processes of the entities. A considerable number of authors emphasise the extensive range of advanced technologies currently in use, which together constitute a natural evolutionary stage within the broader process of digital transformation in freight transport. Among the technologies most frequently identified are cloud computing [40], geolocalisation [41], the Internet of Things [42], and logistics platforms [43]. These four technologies may therefore be regarded as having been implicitly classified as core technologies of Logistics 4.0, with their definitions and their relevance to freight transport delineated in Figure 1. Concurrently, within the set of innovative technological solutions representing prospective directions of development for economic entities, the literature highlights alternative drive technologies [9], artificial intelligence [44], augmented reality [45], autonomous vehicles [46], big data analytics [41], blockchain technology [47], and intelligent transportation systems [48]. These seven technologies can, in turn, be considered the most salient emerging technologies of Logistics 4.0 in the context of freight transport, with their characteristics and references synthesised in Figure 2.

Logistics customer service

A critical analysis of the literature on the subject indicates difficulties in choosing one dominant definition of logistics customer service [73, 74]. The reason is both the multi-attribute nature of services, as well as individual consideration of them through the prism of the specificity of the organisation and its customers [75, 76]. Customer service is a process of integrated management in the sphere of logistics to achieve the desired level of customer satisfaction at the lowest possible cost. In the freight transport sector, customer service can be perceived as the potential of the logistics system of a given entity to meet the disclosed needs of consumers, taking into account the criteria of time, communication, reliability, comprehensiveness and convenience [77, 78]. Ensuring the conditions for the efficient distribution of freight and transport services is essential for the logistics activities of individual companies [79].

At the same time, stopping at the above-mentioned activities more and more often turns out to be only a necessary minimum in the logistics customer service, and it is becoming increasingly important to extend them with additional services that create a unique value for the service buyer [80, 81]. They should be in line with the preferences of customers, along with the accepted standards of logistics customer service by the company. Significant opportunities in this regard are offered by modern information technologies and their application in order to increase the timeliness of deliveries, their flexibility and accessibility, communication with the customer, energy-efficiency of transport means and other elements in the management of logistic customer service in enterprises [82]. Undoubtedly, such technological solutions may serve core and emerging technologies of Logistics 4.0, which can provide logistics support for distribution activities in servicing buyers, which are the culmination of the basic process related to the production and delivery of a product or service according to another definition [83].

Research on the area of logistics customer service is relatively rarely undertaken in scientific publications, especially in recent years [84], and even more rarely in relation to the services provided by freight transport enterprises. A study presented by Huma et al. [85] affirmed the significance of transportation service as a determinant of competitive position on the market. Investigation realized by Mengfei [86] confirmed the cost of remodelling logistics service dedicated to the transport market. Kilibarda et al. [87] research focused on road freight forwarding enterprises and their 120 customers, with main findings about the level of logistics customer service as determined by the structure of the services. Kadłubek [88] analysed determinants of logistics customer service in road cargo transport enterprises in relation to chosen meters of logistics service.

Partly related activities, which is third party logistics or logistics service providers, are definitely a more frequently accepted sector for the implementation of research on customer service in logistics [89]. An example may be the results of

Predominant Core Technologies of Logistics 4.0 in Freight Transport Enterprises

Name	Description	Implementation in Freight Transport Enterprises	Ref.
Cloud Computing	A management-oriented digital infrastructure model that provides organisations with on-demand access to shared and configurable computing resources such as data storage, applications, and processing power, delivered via networked environments to enhance operational flexibility, scalability, and efficiency while reducing the need for internal IT resource management.	Entails the utilisation of network-based computing infrastructures to enable real-time data exchange, process integration, and collaborative management of transport operations, thereby improving operational efficiency, scalability, and decision-making across distributed logistics networks.	[40] [65] [66]
Geolocalisation	A digital management capability that utilises spatial data acquisition and positioning technologies such as GPS, GIS, and IoT systems to identify, monitor, and analyse the real-time geographic position of assets, vehicles, or operations, enabling data-driven coordination, transparency, and optimisation of organisational processes across interconnected environments.	Refers to the use of GPS, GIS, and IoT-based positioning technologies to track, analyse, and manage the real-time movement of vehicles and cargo, enhancing operational visibility, route optimisation, and decision-making efficiency across transport networks.	[41] [67] [68]
Internet of Things	A digitally interconnected system of smart devices, sensors, and communication networks that enable organisations to collect, exchange, and analyse real-time operational data, supporting process integration, automation, and evidence-based decision-making across distributed business and supply chain environments.	Involves the deployment of interconnected sensors, devices, and communication systems to monitor, analyse, and coordinate transport operations in real time, enhancing asset visibility, operational efficiency, and data-driven decision-making throughout the logistics network.	[42] [69] [70]
Logistics Platforms	A collaborative and technology-enabled management framework that connects organisations, assets, and information flows within and across supply chains, facilitating the coordinated planning, execution, and optimisation of logistics activities through standardised data exchange, shared resources, and interoperable digital systems.	Encompasses the use of integrated digital systems that connect carriers, shippers, and service providers to coordinate transport operations, enhance visibility, and optimise resource utilisation through real-time data exchange and collaborative process management.	[43] [71] [72]

Figure 1. Predominant core technologies of Logistics 4.0 in freight transport enterprises

the study on failure situations in logistics customer service in third party logistics branch, described by Huang et al. [90]. A study by Gil-Saura et al. [91] investigates the third-party logistics sector to determine the influence of the performance of logistics customer service on market share and general performance. However, also for the most in-depth areas of customer logistics, references to

Predominant Emerging Technologies of Logistics 4.0 in Freight Transport Enterprises

Name	Description	Implementation in Freight Transport Enterprises	Ref.
Alternative Drive	An energy transformation concept that substitutes conventional combustion-based propulsion with innovative, low- or zero-emission technologies such as electric, hybrid, hydrogen, or gas-powered systems, aimed at enhancing energy efficiency, reducing environmental impact, and supporting the strategic sustainability and competitiveness of transport enterprises.	Entails the adoption of energy-efficient and low-emission propulsion technologies, such as electric, hybrid, hydrogen, or biofuel systems, to reduce operational emissions, optimise energy consumption, and enhance the environmental and economic performance of transport operations within sustainable supply chain frameworks.	[9] [49] [50]
Artificial Intelligence	A machine-based system that, within the confines of human-defined objectives, is capable of making predictions, providing recommendations, or rendering decisions that influence both real and virtual environments.	Denotes the use of data-driven and learning-based methods to support managerial, planning, and decision-making processes aimed at the optimisation of transport operations, fleet governance, demand forecasting, enhancement of safety and energy performance, emissions mitigation, and adaptation of enterprise activities to evolving market and operational conditions.	[51] [52] [53]
Augmented Reality	Technology that integrates elements of the physical environment with virtual data resources in real time, enabling interactive visualisation and analysis of organisational processes within a three-dimensional contextual environment.	Refers to the utilisation of interactive digital visualisation technologies that integrate real-time operational intelligence with the physical operational environment to augment managerial decision-making, optimise fleet and cargo coordination, and enhance the overall efficiency, reliability, and safety of transportation systems.	[45] [54] [55]

Figure 2. Predominant emerging technologies of Logistics 4.0 in freight transport enterprises

Autonomous Vehicles	Transport systems that employ artificial intelligence, sensor-based perception, and algorithmic decision-making to independently perform all driving and operational tasks within a specified operational context, thereby enabling data-driven management, optimisation of transport processes, and strategic coordination of transport resources without the need for direct human control.	Encompasses the integration of self-driving technologies and intelligent control systems into logistics operations to enhance efficiency, safety, and cost-effectiveness through automated transport planning, real-time fleet coordination, and data-driven decision-making.	[56] [57] [58]
Big Data Analytics	A data-driven managerial approach that employs advanced computational, statistical, and machine-learning techniques to extract patterns and actionable insights from large, complex, and fast-changing datasets, thereby enhancing evidence-based decision-making, operational efficiency, and strategic competitiveness within organisational environments.	Entails the utilisation of advanced computational intelligence and large-scale data processing methodologies to synthesise heterogeneous transport information streams, enabling predictive optimisation of logistics networks, enhancement of operational resilience, and data-informed strategic decision-making across the freight domain.	[8] [59] [60]
Blockchain Technology	A decentralised and digitally distributed information system that employs cryptographic mechanisms and consensus protocols to record, authenticate, and synchronise transactional data across a network of participants, thereby ensuring transparency, data integrity, and trust in interorganizational processes without reliance on a central governing entity.	Involves the deployment of decentralised digital ledger systems to ensure transparent, secure, and tamper-proof recording and verification of transport transactions, enabling enhanced traceability, operational efficiency, and trust among logistics stakeholders.	[47] [61] [62]
Intelligent Transportation System	A technology-driven managerial framework that integrates information, communication, and control technologies to support the coordinated planning, monitoring, and optimisation of transport operations, enabling data-informed decision-making, improved safety, and greater efficiency and sustainability in organisational and inter-organisational mobility management.	Dentotes the integration of advanced information, communication, and automation technologies to enable real-time coordination, monitoring, and optimisation of transport operations, thereby enhancing efficiency, safety, and decision-making across the supply chain network.	[48] [63] [64]

Figure 2. Cont. Predominant emerging technologies of Logistics 4.0 in freight transport enterprises

technologies of Logistics 4.0 are rare in the literature. In today's turbulent times, the company's gaining a competitive advantage more and more often results from the use of modern technologies or the introduction of innovative products, also in the area of effective logistics customer service. With the development of technology, customer requirements increase, which results in the need for companies to introduce various facilities for customers, also in the field of Logistics 4.0 [92]. Basically, Logistics 4.0 encompasses a combination of advanced technology in applied information and communication intended to support distinctive progress of the whole transport system in various aspects in freight transport companies. In a customer-oriented approach of the enterprises, the growing level of customer service is considered by Świerczek [93] as one of the predominant components of the fourth industrial revolution, especially determined by information and communication technologies evolvement. Therefore, knowledge of how technology affects consumer notions in regard to service performance seems to become essential. Within freight transport enterprises, unlimited possibilities as buyers, sellers and other stakeholders remain connected to each other through Logistics 4.0 technologies, giving unprecedented power to process and store information and the ability to access knowledge [94]. This, in turn, contributes to the emergence of new business models alongside breakthrough technological solutions integrated into customer service structures, thereby revolutionising transport systems.

Logistics resources

The grounds of resource-based view theory of the enterprises postulate the management of the companies' resources as a constitutional competitive facilitator that can derive an advantage as a result of the value of inimitable resources with no alternative [95]. In the resource-based view literature description of the resource is presented to a greater extent than a business-related determinant of production. As defined by Barney [96], resources are such components of an enterprise that may constitute its strength or weakness and are closely related to the operation of the organisation. According to Lyu et al. [97] and Rushton et al. [98], logistics resources are unique, extraordinary, inimitable assets of an enterprise, crucial for obtaining a competitive advantage in the market.

Logistics resources are understood very broadly and include both tangible and intangible assets [99]. The resources involve various assets of enterprises, including information, knowledge, location of the enterprises, supervised in regard to allowing the enterprise to formulate and implement the optimal strategy for the effectiveness of the company. The fourth industrial revolution aims to unite material and digital resources, i.e. the use of opportunities that are nowadays created in many areas of economic activity by data, analytical tools and mobile technologies [100].

The research focused on logistics resources engaged in proactive development of enterprise performance, also in the area of logistics customer service are presented in the literature among others by Ding et al. [101]. According to the theoretical essentials, Hartmann and De Grahl [102] suggest considering logistics customer service as an enterprise's resource which enables achieving a competitive advantage. In continuation of this theory, within the resource-advantage assumption, in the progressive process theory of competition, the innovations, as well as rudimentary information for customers, are internal and inclusive assumptions presented by Chen et al. [103]. Resources accomplish respective advantages by providing the companies with capabilities to create the service, which, in comparison to the proposal of competitive enterprises, are distinguished by customers to add value or can be arranged within reduced costs. As far as logistics customer service is concerned, from the perspective of Karia [104], it is the extent to which achievable logistics resources are applied to develop a competitive advantage. This dominant position of the enterprise emerges from the service adjoined to the product. Customer orientation and interaction are decisive presumptions of the resource-based view, which is extensively scrutinised as an applicable theoretical viewpoint of Yang [105] for strategic employment of information technology investments.

Moreover, the literature review implies an identification of several categories of resources as significantly consistent with the logistics customer service area, among which three were selected as the most crucial for the paper's aim realisation: logistics information, logistics location and logistics knowledge. The main explanations of these terms are briefly presented below.

One of the primary logistics resources is an intangible resource – logistics information. As introduced by Zu et al. [106], logistics information involve among others, information about: enterprise's real-time demands, purchases, inventories ranks, materials flow, transport flow, as rare and esteemed components of the enterprise's intangible assets. Beynon-Davies [107] prefaces its significance in terms of the transfer of point-of-sale information, prediction information, information about orders, sales, claims and other valuable information referred to pre-transaction, transaction and post-transaction elements of customer service. Information network creation by enterprises may be an innovative and rare solution with the potential of lessening the channels, decreasing intermediaries, and developing immediate contact settlements, which leads to an increase in the level of logistics customer service, as reported by Wong et al. [108]. According to this approach, information flow and communication between employees and customers should seamlessly accelerate the realisation of logistics processes. Engagement of advanced information technology solutions, as Logistics 4.0 proposes, which allow the support of the realisation of logistics processes and activities, appears to represent the currently expected response.

Another logistics resource, classified as a tangible one, is logistics location, which involves admittance to rare and exclusive antecedents of supply, inimitable services, transport and communication route, infrastructure framework, network conveniences, indicated by i.e. Sakai et al. [109]. Especially, transportation enterprises are straightforwardly influenced by their facilities' location and customer service area possibilities, also with regard to a greater extent of progressive technologies supporting transportation. As remarked by Heitz et al. [110], a convenient logistics location is pivotal to shorten delivery time and gain access to distinctive competencies to assure customers' requirements. Thus, as verified by Ballou [111], logistics location decisions influence the level of logistics customer service. For road freight transport enterprises, multi-transportation improvements and supporting leverages achieved through information technology solutions, in reference to favourable logistics location imply lower transportation costs, higher organisational integration, higher processes coordination and their simultaneous occurrence, in general, a more stabilised progress of the transportation system [112].

In logistics, the customer service context logistics location introduces external factors that empower the adaptation of prior potential into preferable logistics customer service and diversified effects of logistics activities, which may arise and support in the prevention or facilitation of mechanisms of logistics customer service. Wang et al. [113] emphasise the function that location prescribed interchangeably as geography performs in logistics customer service, especially in the supply chains arranged in the area of transportation location. For that reason, the logistics location of the enterprises and their partners in supply chains creates the supply chain geography with the function of permission or restriction for the aptitude to turn logistics customer service into leverage in competition.

A further logistics resource is logistics knowledge, understood by i.e. Zhou et al. [114] as a managerial capability which determines an enterprise's latent competency to the extent of proactively conditioning the consequences of logistics resources arranged in maintaining of business processes of enterprises. It is an intangible resource, inimitable and in demand by organisations to facilitate the improvement of basic competencies, confront challenges and intricacies, as well as acquire competitiveness in view of Kianto et al. [115]. As noted by Stachowiak et al. [116], logistics knowledge interpreted as logistics intelligence of the enterprise, which refers to the customers, includes competencies and skills to assemble and assess information about relationships with the customers in the logistics area of the enterprise. Durst et al. [117] investigated the significance of logistics knowledge about the customers in the connection between logistics service customers and logistics service providers, as well as highlighted that logistics knowledge about buyers is the consequence of a very unique interlocution proceeding between logistics service customers and logistics service providers. As not all the data collected by enterprises is valuable from the perspective of the logistics knowledge appropriateness, establishing priorities and human resources indispensable for knowledge development management should contribute to the preferred resources basis arrangement, due to Evangelista et al. [118]. Recognition of the customers' requirements and preferences, which is implied knowledge, raises the level of customer service and increases the customers' satisfaction as reported by Lyu et al. [97]. As freight transport services offered by enterprises evolve to a greater extent involved and knowledge-intensive, growing in the result of accelerating current relationships with customers and organizational learning by recurrence and divergences, they also exploit the knowledge in the arrangement of new information technology solutions, analysed by Iwan et al. [119] as Logistics 4.0 suggests, to create the opportunity in the enterprise to influence the logistics customer service area and raise its level efficiently.

Research objective and hypotheses

Drawing upon the literature review, succinctly and briefly outlined above, existing studies have yet to provide a comprehensive analytical exploration of the influence of technological solutions of Logistics 4.0 on logistics resources, particularly logistics information, logistics location, and logistics knowledge, as well as on logistics customer service in freight transport enterprises. This gap highlights the lack of research at the intersection of core and emerging technologies of Logistics 4.0, logistics resources, and logistics customer service.

Synthesizing the key findings of the literature review presented above and further specifying the scope of the identified research gap, it should first be noted that no publications were identified that propose a classification of technological solutions in the freight transport sector within the Logistics 4.0 paradigm into core and emerging categories. The literature analysis confirms the existence of numerous studies addressing individual technological solutions applied in freight transport; however, these technologies are typically examined in isolation. This applies, inter alia, to studies focusing on cloud computing [40], geolocalisation [41], the Internet of Things [42], and logistics platforms [43], as well as alternative drive technologies [9], artificial intelligence [44], augmented reality [45], autonomous vehicles [46], big data analytics [41], blockchain technology [47], and intelligent transportation systems [48].

Secondly, the literature does not provide a comprehensive examination of core and emerging Logistics 4.0 technologies in freight transport enterprises with regard to their impact on the constructs of logistics resources and logistics customer service. In particular, the area of logistics customer service remains relatively underexplored in the existing literature. The studies most closely related to the scope of the present article concern the analysed sector, inter alia, in publications [85, 87, 88], as well as technological solutions discussed, inter alia, in [89–91]. Issues concerning the linkages between the areas of logistics resources and logistics customer service have been addressed in previous research, among others in studies conducted by [100–105]. However, none of these studies has demonstrated a direct influence of logistics resources on logistics customer service.

Accordingly, the research question is formulated as follows:

- RQ: What is the influence of core and emerging technologies of Logistics 4.0 on logistics resources and logistics customer service in freight transport enterprises?

In response to the above question, the following hypotheses are proposed:

- H1. Core technologies of Logistics 4.0 are positively associated with logistics resources in freight transport enterprises.
- H2. Emerging technologies of Logistics 4.0 are positively associated with logistics resources in freight transport enterprises.
- H3. Core technologies of Logistics 4.0 are positively associated with logistics customer service in freight transport enterprises.
- H4. Emerging technologies of Logistics 4.0 are positively associated with logistics customer service in freight transport enterprises.
- H5. Logistics resources positively influence logistics customer service in freight transport enterprises.

In Figure 3, we present the conceptual model outlining the hypothesised relationships among the main areas.

MATERIALS AND METHODS

The primary objective of the research was to examine the impact exerted by selected core and emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service as determined by alignment with chosen logistics resources.

Empirical data were acquired from freight transport enterprises located in Poland through

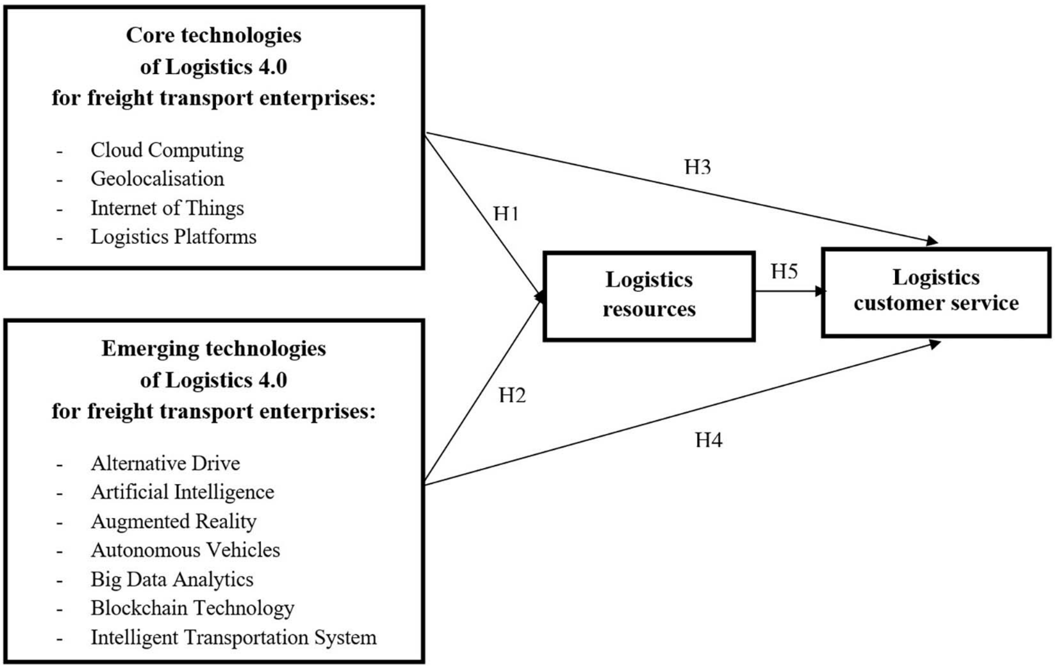

Figure 3. Conceptual framework illustrating the hypothesised relationships

the application of a survey methodology [120]. The investigation encompassed enterprises listed in the REGON register administered by the Polish Central Statistical Office that are engaged in the provision of commercial road freight transport services. Empirical data were gathered through a stratified sampling procedure designed to ensure an appropriate representation of the underlying population. The sampling framework incorporated several relevant dimensions, namely industry segment, geographical distribution, and firm size, operationalized in terms of the number of employees. The composition of the sample within each dimension was established on the basis of the most recent statistical data released by the Central Statistical Office. In light of the distribution of respondents across the identified categories, as well as methodological considerations concerning the association between sample size and the robustness of path modelling estimates, the resulting dataset was considered suitable for further analytical procedures.The research population was deliberately limited to individuals holding managerial positions, under the assumption that they possess the most extensive and substantive knowledge of organisational operations, particularly in relation to the analytical dimensions delineated within the scope of the study's objective framework.

The inquiry instrument was developed based on an in-depth review of the relevant literature. Data collection was conducted over a five-month period (August – December 2023) using the Computer-Assisted Telephone Interviewing (CATI) technique, targeting 655 representatives of freight transport enterprises. Of the total responses gathered, 195 questionnaires were excluded from the analytical sample due to incomplete or inaccurate data. Consequently, the final dataset comprised 460 fully completed and valid interviews, which served as the foundation for the empirical analysis, corresponding to a response rate of 70.2%. While the study does not aim at strict statistical representativeness, the obtained sample provides a meaningful representation of freight transport enterprises active in the analyzed sector.

A pivotal component of the questionnaire was meticulously designed to capture data on all variables encompassed within the conceptual model, incorporating construct items pertaining to: four core technologies of Logistics 4.0 in freight transport enterprises, seven emerging technologies of Logistics 4.0 in freight transport enterprises, seven categories of logistics resources and four categories of logistics customer service (Table 1). The measurement items used to operationalize the construct of logistics customer service were adapted from previously validated scales reported in prior studies by [26, 73, 111]. Similarly, the items used for the operationalization of the construct logistics resources were adapted from validated measurement scales reported in

Table 1. Operationalisation of constructs

Variables	Acronyms	Constructs	Ref.
Core technologies of Logistics 4.0 in freight transport enterprises	CTL4.0.1	Our company uses cloud computing integrate logistics operations, allowing seamless data exchange between dispatchers, drivers, and customers.	[40] [41] [42] [43]
	CTL4.0.2	Our company uses geolocalisation to provide real-time visibility of vehicle positions, helping react quickly to delays and improve delivery accuracy.	
	CTL4.0.3	Our company uses the Internet of Things to collect real-time data from connected vehicles and cargo, enabling predictive maintenance and enhanced shipment security.	
	CTL4.0.4	Our company uses logistics platforms to streamline coordination across the supply chain by connecting carriers, shippers, and warehouses through a unified digital environment.	
Emerging technologies of Logistics 4.0 in freight transport enterprises	ETL4.0.1	Our company uses alternative drives to reduce fuel costs and meet environmental regulations by shifting to electric or low-emission vehicles.	[9] [41] [44] [45] [46] [48]
	ETL4.0.2	Our company uses artificial intelligence to support forecasting demand, automating dispatch decisions, and detecting anomalies in delivery patterns.	
	ETL4.0.3	Our company uses augmented reality to support warehouse operations through interactive visual guidance, thereby increasing process accuracy and operational efficiency.	
	ETL4.0.4	Our company uses autonomous vehicles to enhance transport efficiency, reduce human error, and enable continuous operation with minimal manual intervention.	
	ETL4.0.5	Our company uses big data analytics to identify patterns in large volumes of logistics data, facilitating informed decision-making, demand forecasting, and performance optimisation.	
	ETL4.0.6	Our company uses blockchain technology to ensure transparency, traceability, and security in logistics transactions and documentation across the supply chain.	
	ETL4.0.7	Our company uses an intelligent transportation system to dynamically manage traffic flows, optimise routing decisions, and enhance the overall efficiency and safety of freight mobility.	
Logistics resources	LR.1	In our company, the exchange of information and communication with both employees and customers significantly expedites the execution of logistics operations.	[98] [104] [106] [109] [117]
	LR.2	Our company has implemented information systems that enable the swift and effective completion of orders.	
	LR.3	Our company has established information systems and organisational procedures that facilitate effective oversight of strategic decision-making processes.	
	LR.4	In our company, utilisation of the organisational infrastructure is readily available and efficiently maintained.	
	LR.5	In our company, the availability of the services offered by the enterprise is ensured in a convenient and effective manner.	
	LR.6	In our company, knowledge concerning the enterprise's range of services, the processes implemented, and their associated issues is easily accessible.	
	LR.7	In our company, knowledge regarding the organisation's customers, their expectations, and challenges is readily accessible.	
Logistics customer service	LCS.1	In our company, the evaluation of customer support is based on a comprehensive set of metrics, encompassing transit and delivery duration, adaptability of services, service frequency, precision and dependability of transport operations, and user-friendliness of ordering procedures.	[26] [73] [111]
	LCS.2	Our company assesses the level of customer satisfaction through systematic evaluation methods.	
	LCS.3	Our company effectively manages relationships with existing customers while actively engaging in the acquisition of new business contacts.	
	LCS.4	Our company provides transport services that contribute to the growth of sales and market reach.	

earlier studies by [98, 104, 106, 109, 117], and were slightly modified to better reflect the context of freight transport enterprises. Due to the novelty of the research area, validated measurement scales were not available for the constructs core technologies of Logistics 4.0 and emerging technologies of Logistics 4.0. Therefore, the measurement items for these constructs were developed by the authors based on an extensive review of the literature, with particular consideration given to the findings reported by [40–43] for core technologies of Logistics 4.0, and by [9, 41, 44–46, 48] for emerging technologies of Logistics 4.0 in freight transport companies.

A five-point Likert-type scale was employed for all validated measurement items, where 1 means „I strongly disagree", and 5 means „I strongly agree". Moreover, the questionnaire encompassed items aimed at capturing crucial organisational attributes of the participating organisations, with the corresponding results detailed in Table 2.

Following the identification of all required measurement instruments, a pilot study was conducted to validate the appropriateness of the proposed research procedure and to identify and eliminate potential deficiencies within the adopted item set.

Within the adopted research procedure, a multi-stage methodological approach was applied. Initially, confirmatory factor analysis was performed to assess the reliability and validity of the proposed constructs [121]. In the subsequent phase, the collected data were analysed using the Structural Equation Modelling – Partial Least Squares (SEM-PLS) method [122], [123], employing SPSS Amos version 26.0 and the R package *lavaan* [124]. In the final stage of the research procedure, a post-hoc analysis was conducted to identify similarities in the observed effects and to further interpret the underlying patterns within the model's relationships of core technologies of Logistics 4.0 and emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service.

Within the confines of this article, the following section presents only the principal findings of the research undertaken.

RESULTS OF RESEARCH

Evaluation of the measurement model

Confirmatory factor analysis (CFA) was performed as a methodological approach to evaluate the reliability and validity of the constructs, in line with analytical frameworks proposed by, among others, Ross et al. [121]. The construct validity of the measurement items was ensured through their theoretical grounding in prior literature and the adaptation of validated scales where available, while newly developed items were carefully derived from an extensive literature review to ensure their conceptual consistency with the studied constructs. Considering the proposed model, the data demonstrated an acceptable level of model fit, as presented in Table 3, with $X^2(162) = 181.66$, RMSEA = 0.045, NFI = 0.91, CFI = 0.96, SRMR = 0.047. As indicated in Table 3, the obtained values for Cronbach's alpha exceeded the conventional threshold of 0.70, consistent with the methodological standards articulated by Fornell and Larcker [125]. Based on the factor loadings, all estimated values for the adopted measurement items exceeded the threshold of 0.40, indicating substantial associations with the corresponding latent constructs, in line with the criteria proposed by Hair et al. [122] and Guenther et al. [126]. Concurrently, the values of composite reliability and average variance extracted for all constructs exceeded the recommended cut-off points of 0.80 and 0.50, as suggested by Fornell and Larcker [125], thereby confirming the adequacy of the measurement model for subsequent structural analysis.

Following the methodological guidelines outlined by Schwarz et al. [127] concerning the appropriate handling of common method

Table 2. Profile of respondent organisations

Feature	Response	Number of enterprises
Function in the organisation	Top-level executive	24
	Manager	276
	IT systems coordinator	160
Principal business activity of the organisation	Freight transportation services	345
	Freight forwarding services	97
	Third-party logistics provision	18
Size of the organisation	Large-sized	9
	Medium-sized	83
	Small-sized	368

Table 3. Measurement model

Element	Loading (λ)	T-value* (t)	Mean (M)	Standard deviation (SD)	Average variance extracted (AVE)	Composite reliability (CR)	Cronbach's alpha (α)
Core technologies of Logistics 4.0 in freight transport enterprises							
CTL4.0.1	0.782	13.32	3.04	1.39	0.617	0.868	0.931
CTL4.0.2	0.761	13.21	3.00	1.30			
CTL4.0.3	0.832	13.63	3.09	1.37			
CTL4.0.4	0.879	12.78	3.07	1.41			
Emerging technologies of Logistics 4.0 in freight transport enterprises							
ETL4.0.1	0.804	10.66	3.08	1.40	0.643	0.897	0.865
ETL4.0.2	0.798	10.87	3.03	1.44			
ETL4.0.3	0.792	11.36	3.06	1.40			
ETL4.0.4	0.803	10.96	3.09	1.48			
ETL4.0.5	0.787	12.89	3.04	1.39			
ETL4.0.6	0.819	13.29	3.04	1.36			
ETL4.0.7	0.788	12.96	3.08	1.41			
Logistics resources							
LR.1	0.803	11.84	2.99	1.28	0.610	0.896	0.907
LR.2	0.806	12.27	3.02	1.30			
LR.3	0.741	12.38	3.05	1.32			
LR.4	0.758	11.15	3.01	1.33			
LR.5	0.743	10.44	3.07	1.37			
LR.6	0.738	10.18	2.96	1.38			
LR.7	0.759	11.24	2.99	1.33			
Logistics customer service							
LCS.1	0.738	9.57	3.15	1.36	0.549	0.819	0.882
LCS.2	0.687	11.33	3.18	1.34			
LCS.3	0.776	11.94	3.10	1.27			
LCS.4	0.665	10.07	3.09	1.26			

Note: * Significant at the $p < 0.01$ level.

variance, the designated procedural steps were employed. In the preliminary phase, Harman's single-factor analysis was conducted, revealing that no single factor explained more than 30% of the shared variance. Subsequently, in line with the recommendations of Tabachnick and Fidell [128], the analysis confirmed the absence of excessively high inter-construct correlations. Thereafter, adhering to the guidelines proposed by Lindell and Whitney [129], the marker variable technique was applied to assess the presence of latent common method bias. A three-item measure was utilised to capture respondents' positive inclination, designated as a method variance marker as per the approach proposed by Lindell and Whitney [129]. Based on the adjustment using the smallest positive correlation between the marker variable and the other constructs, the findings revealed that none of the examined correlations lost statistical significance after the correction was applied. As a result of these findings, it was determined that the dataset was not markedly compromised by common method variance. Following this, the marker variable approach was applied within a confirmatory factor analysis framework, with chi-square (X^2) = 259.28, goodness of fit values (df) = 230, model comparison tests (NFI) = 0.93, and five models were formulated. Consistent with the framework outlined by Richins [130], the results indicated that common method bias did not exert a statistically significant influence on the integrity of the data structure.

Subsequently, a full collinearity assessment was conducted, yielding variance inflation factor (VIF) values below 3.3 for all latent variables within the structural equation model, thereby confirming the absence of common method bias in the analysed data, as outlined by Westland [123]. The key outcomes of the model, as presented in Table 4, were thoroughly examined. The structural equation model was assessed following the generation of a resampled dataset comprising 5000 bootstrap iterations with replacement, derived from the original sample. Through successive analytical procedures encompassing the evaluation of collinearity diagnostics, model fit indices, explanatory capacity, and the statistical significance of structural path coefficients, the resulting evidence substantiated the overall validity of the proposed model. Ultimately, the adjusted R^2 values derived for the latent constructs amounted to 0.31 in the case of logistics resources and 0.52 for logistics customer service, indicating that the implementation of both core and emerging Logistics 4.0 technologies within freight transport enterprises significantly shapes the development of logistics resources, thereby validating the hypothesised relationships embedded in the conceptual model. Furthermore, the analytical findings substantiated a direct and meaningful linkage between the adoption of core Logistics 4.0 technologies and the performance of logistics customer service ($\beta = 0.481$; $p < 0.001$). This can be explained by their high level of technological maturity and their widespread use in the day-to-day operations of freight transport enterprises. These technologies are already well integrated with logistics processes, directly supporting key elements of customer service such as delivery timeliness, service reliability, and the availability of shipment information. Concurrently, the assumption that emerging Logistics 4.0 technologies exert a positive effect on logistics customer service was not empirically validated ($\beta = 0.001$; $p = 0.979$), but they exert a significant indirect effect through logistics resources ($\beta = 0.131$; $p < 0.001$). This result may be associated with the relatively early stage of development and implementation of these technologies in the freight transport sector. In practice, their application initially contributes to the development of firms' logistics resources, such as information infrastructure and analytical capabilities, which may only subsequently translate into improvements in logistics customer service. The lack of empirical support for this assumption may be explained by their still limited maturity and incomplete diffusion across freight transport operations, which corresponds with empirical findings documented, inter alia, by the Polish Road Transport Institute [36], PwC [37], TLP [38], and Trans.Eu [39]. Many such technologies are implemented in pilot or transitional phases, during which organisational learning, process adjustments, and integration challenges may temporarily neutralise or obscure potential service improvements. Furthermore, expectations regarding the application of these technologies in ongoing business operations are likely to be perceived by entrepreneurs as a long-term and relatively distant prospect, yielding priority to current activities in well-established and thoroughly recognised areas. Additionally, the analysis revealed that logistics resources serve as a mediating variable in the relationship between both core and emerging Logistics 4.0 technologies and logistics customer service.

Table 4. Results of hypotheses testing

Hypothesis	Effect type	Pathway	Unstandarized coefficient B	Standarized coefficient β	P-value
H1	Unmediated	Core technologies of Logistics 4.0 → Logistics resources	0.524	0.529	<0.001
H2	Unmediated	Emerging technologies of Logistics 4.0 → Logistics resources	0.323	0.337	<0.001
H3	Unmediated	Core technologies of Logistics 4.0 → Logistics customer service	0.442	0.481	<0.001
H4	Unmediated	Emerging technologies of Logistics 4.0 → Logistics customer service	0.001	0.001	0.979
H5	Unmediated	Logistics resources → Logistics customer service	0.349	0.392	<0.001
	Mediated	Core technologies of Logistics 4.0 → Logistics customer service	0.193	0.199	<0.001
	Mediated	Emerging technologies of Logistics 4.0 → Logistics customer service	0.119	0.131	<0.001

Post-hoc inquiry

In the next step of the research procedure, the post-hoc analysis was intended to distinguish the comparison of the impacts of core technologies of Logistics 4.0 and emerging technological solutions in freight transport enterprises on logistics customer service. As the results of hypotheses testing presented in Table 4 indicate that, in addition to direct effects, logistics resources serve as a mediating factor that indirectly improves logistics customer service, we focused on a more detailed exploration of this area. Drawing upon a set of seven indicators representing logistics resources, LR.1 – LR.7, as detailed in Table 1, the present investigation extends the conceptual treatment of this construct through a structured differentiation of its internal components. Consistent with the theoretical arguments advanced in the literature review, logistics resources are reconceptualized as a multidimensional construct comprising three analytically distinct facets: logistics information LRI, operationalized through three construct items LR.1 – LR.3; logistics location LRL, operationalized through two construct items LR.4 – LR.5; and logistics knowledge LRK, operationalized through two construct items LR.6 – LR.7. The CR, AVE, and α indices for these constructs were evaluated and demonstrated compliance with recommended threshold levels. The analytical framework was subjected to empirical scrutiny through the application of hierarchical multiple regression techniques, with the resulting estimates reported in Table 5. Prior to hypothesis testing, a series of diagnostic procedures was undertaken. Specifically, the Kolmogorov-Smirnov test provided statistical support for the assumption of normally distributed

Table 5. Results of hierarchical multiple regression

Outcome variable	Logistics customer service				
Models	1	2	3	4	5
Effects					
CTL4.0	0.249**	0.246**	0.228**	0.251**	0.299**
ETL4.0	0.238**	0.218**	0.223**	0.176**	0.211*
Moderators					
LRI		-0.003	-0.003	-0.021	-0.028
LRL		0.023	0.012	0.019	0.009
LRK		0.039	0.081	0.076	0.079
Interactions					
CTL4.0* LRI			-0.139**		
ETL4.0* LRI			0.028		
CTL4.0* LRL				-0.112**	
ETL4.0* LRL				-0.078*	
CTL4.0* LRK					0.021
ETL4.0* LRK					-0.208**
Coefficient of determinantion (R^2)	0.013	0.227	0.239	0.299	0.358
F-statistic (F)	0.690	10.095**	6.194**	6.598**	8.190**
Change in R-squared (ΔR^2)		0.197	0.005	0.052	0.136
Change in F-statistic (ΔF)		22.873**	0.280	6.312**	15.894**
Maximum Variance Inflation Factor (VIFmax)	1.178	1.526	1.622	1.657	1.680
Kolmogorov-Smirnov test	0.055	0.039	0.027	0.048	0.039
	(p=0.06)	(p=0.020)	(p=0.020)	(p=0.020)	(p=0.020)
Breusch-Pagan test	0.05	1.00	0.45	0.05	0.20
	(p=0.70)	(p=0.30)	(p=0.55)	(p=0.60)	(p=0.75)
White test	5.08	17.86	35.64	56.17	49.24
	(p=0.68)	(p=0.39)	(p=0.73)	(p=0.58)	(p=0.69)

Note: * significant value at 0.05; ** significant value at 0.01.

residuals. Subsequently, the implementation of White's test alongside the Breusch-Pagan procedure yielded no evidence of heteroscedasticity, thereby substantiating the homoscedastic nature of the error terms. Finally, variance inflation factor diagnostics confirmed that intercorrelations among the explanatory variables remained well within acceptable thresholds, indicating that multicollinearity did not compromise the integrity of the regression estimates.

The literature indications presented by Alken and West [131] were used, according to which the sampling data were separated into two groups after applying the moderator's mean value. Extreme levels of moderators were determined as one common discrepancy exceeding and falling below the mean. For the two groups, the regressions were proceeded and afterwards the path coefficients were assembled in comparison (Table 6 and Figure 4).

The data presented in Table 6 and Figure 4 are consistent with moderating effects of logistics information for core technologies of Logistics 4.0 in freight transport enterprises ($\beta = 0.028$, n.s.) and emerging technologies of Logistics 4.0 in freight transport enterprises ($\beta = -0.139$, $p < 0.01$). The acquired results exposed the dependence that logistics information turns from low to high; the impact of core technologies in freight transport enterprises does not evolve fundamentally, nevertheless, the impact of emerging technologies decreases primarily. Respectively, when the logistics information is low, the impact of emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service is significantly higher than the impact of core technologies of Logistics 4.0 ($t = 12.487$). Moreover, if logistics information is high, the value of core technologies of Logistics 4.0 in freight transport enterprises is to some extent, insignificantly higher than the value of emerging technologies of Logistics 4.0 in freight transport enterprises ($t = 1.890$).

The arrangement of the moderating effects of logistics knowledge is opposite to the above findings of logistics information. If logistics knowledge turns from low to high, the impact of emerging technologies of Logistics 4.0 in freight transport enterprises does not evolve fundamentally ($\beta = 0.021$, n.s.), and the impact of core technologies of Logistics 4.0 in freight transport enterprises decreases primarily ($\beta = -0.208$, $p< 0.01$). If the logistics knowledge is low, the impact of core technologies of Logistics 4.0 in freight transport enterprises is significantly higher than the impact of emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service ($t = -10.620$). Moreover, if logistics knowledge is high, the value of core technologies of Logistics 4.0 in freight transport enterprises is, to some extent, insignificantly higher than the value of emerging technologies of Logistics 4.0 in freight transport enterprises ($t = -0.509$).

With reference to logistics location, the moderating effects of both core and emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service declines primarily (accordingly $\beta = -0.112$, $p< 0.01$; $\beta = -0.078$, $p< 0.05$) if logistics location turns from low to high. If logistics location is low, the effect of core technologies of Logistics 4.0 in freight transport enterprises is more intimate than the impact of emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service ($t = -3.128$). Moreover, if logistics location is high, the impact of core technologies of Logistics 4.0 in freight transport enterprises is, to some extent, insignificantly lower than the value of the emerging technologies of Logistics 4.0 in freight transport enterprises ($t = 0.975$).

Table 6. Comparison between core technologies of Logistics 4.0 and emerging technologies of Logistics 4.0 in freight transport enterprises: quantitative results

Parameter	All	Logistics information		Logistics location		Logistics knowledge	
		Low	High	Low	High	Low	High
Core technologies of Logistics 4.0 in freight transport enterprises	0.250	0.711	0.226	0.486	0.136	0.114	0.115
Emerging technologies of Logistics 4.0 in freight transport enterprises	0.234	0.050	0.034	0.672	0.104	0.684	0.152
T-value	1.621	12.487	1.890	-3.128	0.975	-10.620	-0.509

Note: * $p < 0.01$, n.s. – not significant.

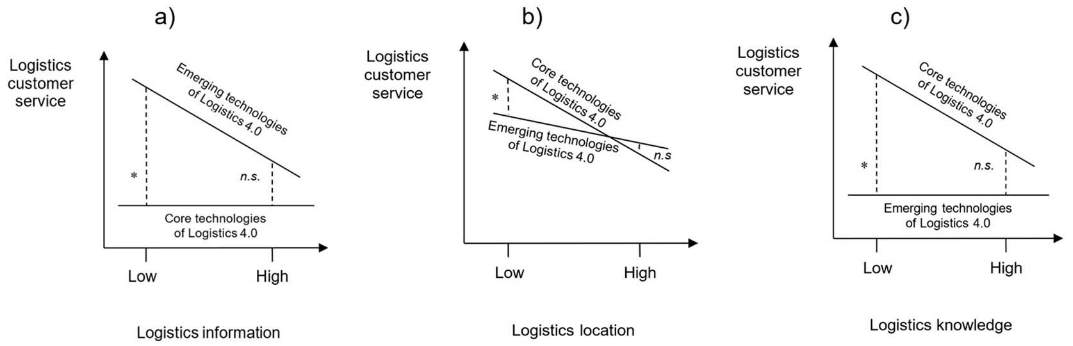

Figure 4. Comparison between core technologies of Logistics 4.0 and emerging technologies of Logistics 4.0 in freight transport enterprises: illustrative results. * - $p< 0.01$, n.s. – not significant

DISCUSSION

This paper examines the significance of selected technologies of Logistics 4.0, both core and emerging, intended to support logistics resources and logistics customer service in freight transport sector activities. Within this scope, the paper provides empirical substantiation of the influence of technological solutions associated with Logistics 4.0 on logistics resources, as well as on outcomes achieved in the domain of logistics customer service, thereby constituting a relevant contribution to the extant literature.

Notwithstanding the acknowledged implicit value of previously published findings concerning diverse information and communication technology solutions applied within freight transport enterprises and in the provision of services to their customers, the literature review indicates that only a limited number of studies have addressed the specific enabling role of technologies of Logistics 4.0. Although references to such technological solutions remain exceptionally scarce in literature devoted to advanced issues of logistics customer service, when they are considered within the broader category of information technology solutions, contributions consistent with the empirical results obtained in this paper can be identified. Comparable conclusions have likewise been reported in studies on information technologies, among others, by Hryhorak et al. [132] and Szymczak [133].

A further theoretical contribution derived from the findings presented in the paper pertains to the empirically evidenced beneficial effect of selected technologies of Logistics 4.0 on logistics resources, which may consequently exert a pronounced influence on the overall scope of achievements realised within the customer service area according to Kawa and Maryniak [134]. Chosen core technologies of Logistics 4.0 primarily enhance the efficiency, visibility, and integration of existing logistics resources. Their overall effect is evolutionary, strengthening operational control and connectivity without fundamentally altering the structure of logistics systems. Simultaneously, emerging technologies of Logistics 4.0 exert a more transformative influence by reshaping the nature and configuration of logistics resources. They enable automation, predictive and autonomous decision-making, new energy solutions, and decentralised coordination mechanisms, which redefine the roles of physical assets, human labour, and information infrastructures. Their impact is strategic and structural, driving new business models, competencies, and system architectures.

Likewise, core technologies of Logistics 4.0 enhance logistics customer service primarily by improving service reliability, transparency, and responsiveness. Real-time tracking, integrated data environments, and digital coordination platforms enable more accurate delivery information, faster communication, and better handling of customer inquiries and service adjustments. As a result, customer service performance is strengthened through greater operational visibility, consistency, and process efficiency. Interpretatively, these findings do not necessarily refute the theoretical potential of emerging Logistics 4.0 technologies to enhance logistics customer service. Rather, they suggest that their service-related benefits are conditional, temporally delayed, and strongly dependent on implementation depth, organisational readiness, and systemic integration. The realisation of service gains is largely contingent upon the development of appropriate competencies, process redesign, and strategic alignment. Consequently, the absence of statistically significant effects should be interpreted not as a negation of their potential, but rather as evidence that their service-related benefits are conditional and subject to temporal and organisational contingencies.

In addition to the effects outlined above, the study also reveals important implications for practitioners, particularly for managers in freight transport enterprises. The findings suggest that the deliberate selection and implementation of Logistics 4.0 technologies supporting both core and emerging solutions can strengthen logistics resources related to customer service and support the development of logistics capabilities. From a managerial perspective, core technologies primarily optimise and digitalise existing logistics processes and resource configurations, enabling incremental improvements in operational efficiency and service performance. In contrast, emerging technologies have the potential to fundamentally transform and reconfigure logistics resources, enabling more systemic and potentially disruptive changes. Therefore, the results may support managers in planning technology adoption and investment decisions, indicating that organisations should combine technologies that enhance existing operations with those that enable deeper transformation of logistics capabilities. The findings may also point to prospective directions for investment in selected Logistics 4.0 technologies by highlighting the novel benefits associated with their implementation, as likewise posited by Cichosz et al. [94].

It has also been demonstrated that both core and emerging technologies of Logistics 4.0 within freight transport enterprises constitute valuable instruments facilitating access to critical information relevant to logistics customer service. Another dimension of logistics customer service that benefits from the application of technological solutions of Logistics 4.0 in freight transport enterprises is the development and sustained maintenance of customer relationships. Comparable findings were reported by Modica et al. [9] and Vida et al. [135] in their studies on the development of transportation processes via Logistics 4.0 implementation.

A further noteworthy insight relates to the role of both core and emerging technologies of Logistics 4.0 in freight transport enterprises, which warrant close alignment with logistics resources due to their extensive capacity to reinforce logistics customer service. Particular emphasis should be placed on emerging technologies of Logistics 4.0 in freight transport enterprises, together with the relatively diminished relevance of logistics location and the pronounced importance of logistics information as logistics resources instrumental in advancing logistics customer service. Concurrently, the findings demonstrate that core technologies of Logistics 4.0 in freight transport enterprises exhibit greater effectiveness in strengthening logistics customer service under conditions in which the enterprise's logistics location does not occupy a leading position and where logistics knowledge remains at a moderate level within the organisation. Overall, both core and emerging technologies of Logistics 4.0 in freight transport enterprises contribute to the enhancement of logistics customer service; however, their relative suitability is contingent upon the configuration of logistics resources and the specific requirements of the enterprise's customers. Enterprises characterised by comparatively limited logistics knowledge should therefore prioritise core technologies of Logistics 4.0 in freight transport enterprises to support logistics customer service. In contrast, organisations possessing more advanced logistics information should give consideration to emerging technologies of Logistics 4.0 as a means of further advancing logistics customer service.

Nevertheless, the study is subject to several limitations that may serve to inform future research directions. First, the research procedure incorporated only three selected categories of logistics resources, specifically logistics information, logistics location and logistics knowledge, whose potential effects were assessed. However, the influence of core and emerging technologies of Logistics 4.0 in freight transport enterprises on logistics customer service may also be associated with other logistics resources not included in the present scope of analysis.

A further limitation concerns the technological scope adopted in the study, which encompassed only selected core and emerging technological solutions of technologies of Logistics 4.0 in freight transport enterprises. These were examined within two defined groupings: four core technologies and seven distinct emerging technologies. The wide spectrum of available technological solutions suggests that the range considered in the study could be extended, both with respect to the specific operational domains in which core and emerging technologies of Logistics 4.0 are applied, and to other important areas supported by technologies of Logistics 4.0.

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