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Smart City Logistics on the Basis of Digital Tools for ESG Goals Achievement

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Abstract: The development of modern logistics systems requires state-of-the-art solutions for simultaneously achieving sustainable development goals and ambitious business targets. On this issue, the challenge of implementing digital technologies in social life, in particular in smart cities, deserves special attention. The diversified application of Industry 4.0 doctrine and digital shadow penetration to all fields of socioeconomic systems highlights the gaps in the design, control, and efficiency assessment of digital tools in the logistics of smart cities. Another challenge concerns the need to consider environmental, social, and governance (ESG) principles amid the deployment of harmonic digital tools within urban territories. All these issues require a complex methodological approach toward understanding the role of IT in the modern economy through an ESG prism. The article contains a contemporary literature review on the related topic and the conceptual framework of city logistics digitalization under ESG perspectives and constraints. The mathematical model proposed by the researchers enables a multidimensional design of digital solution applications within smart city logistics performance. The designed discrete stochastic model is eligible for scaling toward and the further development of variables other than the key ones mentioned above. The mathematical formalization of the proposed model considers the distribution of the limited budgeting of administrative branches within city logistics, highlighting the research relevance in connection with the ESG principles.

Keywords: smart city logistics; omnichannel logistics; ESG principles; digitalization; 4.0 logistics

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1. Introduction

Japan's experience in building an Industry 5.0 society brings ideas about the possibility of reaching that ambitious goal to other countries [1,2]. Social prosperity and economic growth are nowadays tightly correlated with interdisciplinary doctrines and integrated approaches toward sustainable development. The principles of ESG (environmental, social, and governance) reflect the modern challenges and opportunities that our society has faced. Social development is impossible without technological improvements, concerned governing, and environmentally friendly solutions in all fields of human activities. As an integrated tool of socioeconomic development and efficient resource management, logistics is considered an innovative approach toward sustainable growth, increasing quality of life. By implementing digital technologies and smart solutions in city logistics, in particular, we may contribute to the prosperity of society and sustainable development.

The problem of the research is defining possible ways that IT can contribute to environmental, social, and governing excellence in city logistics. The high importance of digitalization in business and engineering is nowadays not included in any discussions. Nevertheless, there is still no comprehensive methodology directly reflecting the correlation between the IT development level and the key drivers of the ESG principles.

Thus, the research aims to develop a coherent concept of the contribution of smart city logistics with ESG principles and digital tools. The novelty is focused on designing a conceptual bridge between digitalization and ESG dimensions to make a sufficient contribution to smart city logistics. Note that there are different approaches to defining the term *city logistics*: some authors have considered cargo and passenger flows [1,2], while some specialists have included cargo flows and related logistics infrastructure [3]. We take the second approach, with a focus on the retail sector. The essential elements of supply chain infrastructure, such as warehouses, docking centers, etc., are nowadays modified according to the most crucial digital solutions, such as using robots, interactive algorithms, automotive control, shifting to the cyberphysical system, etc. Some specialists [4] have emphasized economic and ecological tradeoffs first, not considering the social aspects. At the same time, there is a research gap in identifying the critical roles that the digitalization of logistics and physical distribution play in sustainable city development. To reach the social development goals, the focus should be on smart solutions of city logistics as the most contributive field toward achieving ESG principles. The practical application of the research is to define the role of digital tools in developing the fundamental ESG principles in city logistics.

2. Literature Review

A content analysis on literature sources allows for concluding that the ESG concept presents a balanced approach to reasonable resource consumption within many human activities. Logistics, as an integrated transport management tool, physical distribution, and cooperation, especially corresponds to the ESG principles. For economic purposes, a closed-loop supply chain and the management of returnable product distribution significantly benefit sustainable development. According to [4], remanufacturing as a part of a sustainable development plan occupies top-level costs equal to manufacturing and order processing. Partly, this might be explained by the modern transformation of industrial production systems [2]. Digitalization leads to more transparent business models with intelligent manufacturing, decentralized production plans, and increased costs to achieve sustainable development goals. At the same time, apart from manufacturing and related processes, sustainability penetrates all the supply chain echelons [5]. However, how can specific tools be implemented in practice to achieve high sustainability goals? According to the survey conducted in 2020, published at (https://www.statista.com/, accessed date 10 October 2022), the most common digital tools used for the implementation of sustainable development programs in Russia in 2020 are the following:

- Technologies for collecting, processing, and analyzing large numbers of data.
- Information security tools and services.
- Digital workplaces.
- Artificial intelligence.
- Digitalization of energy.
- End-to-end automation, production, and management process integration into one information system.
- Robotization of production.
- Cloud and edge technologies.

- Radio frequency identification technologies.
- Sales of industrial goods via the internet.
- Internet of Things (IoT), open production, 3D printing.
- Blockchain.

Leading positions are occupied by data-processing tools and information security tools. Most perspectives on further development consider IoT, 3D printing, and cloud logistics as the most beneficial among the social, economic, and environmental principles. We propose conducting a PESTLE analysis to define specific ways of contributing to ESG goals by digitalizing logistics activities (Figure 1). The result has proved the authors' idea that logistics and supply chain management significantly influence all aspects of society. It is impossible to consider city logistics outside of digital trends.

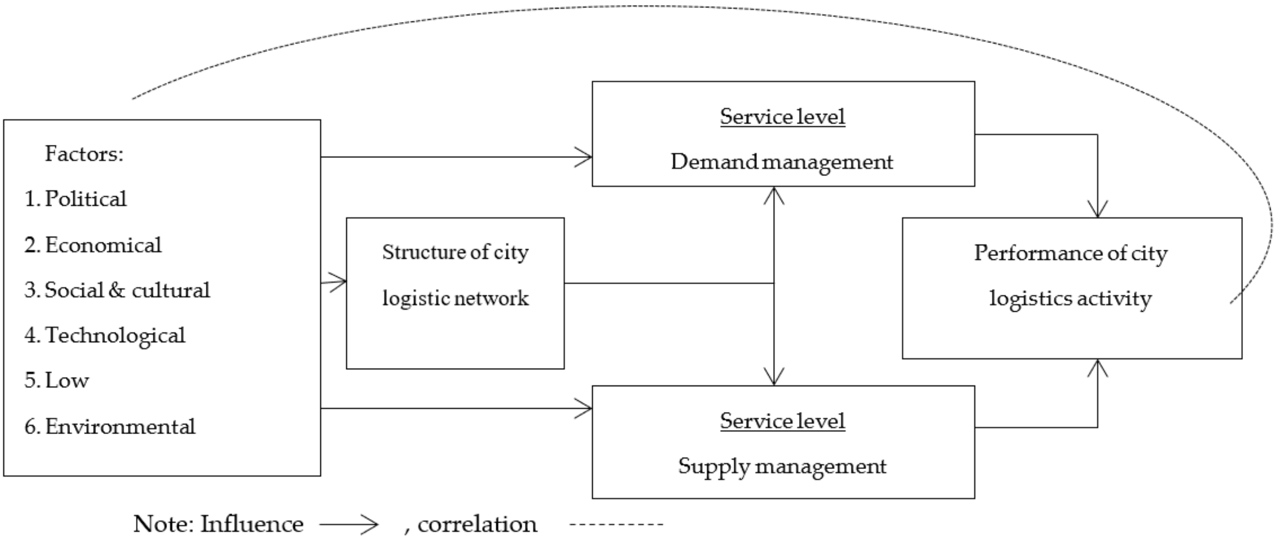

Figure 1. Influence of external factors on city logistics performance (developed by the authors).

As we can see from Table 1, the focus is on advanced processes. At the same time, considering elements of logistics infrastructure for their possible digitalization is also essential.

Table 1. Correlation between digital technologies in supply, manufacturing and distribution with ESG goals (proposed by the authors).

Advanced Technologies	*Description*	*ESG Dimension*	*Ref.*
Autonomous Robots	Evolving utility, increasing autonomy, flexibility, and interaction with humans and other robots	Environmental	[5–7]
Simulation	Improve plant operations, creating a virtual model of the factory, including machines, products, and humans, also called digital twins	Social	[8,9]
Horizontal and Vertical Systems Integration	IT system integration in the entire supply chain, creating data-integration networks and internal cross-function integration	Governance	[9–14]
Industrial IoT	Devices with embedded computing communicating and interacting in real time	Social	[9,11,12]
Cybersecurity	Securing reliable communication and information flows	Governance	[15,16]
Cloud Logistics	Data-driven services and data sharing across different sites deployed in the cloud	Governance	[17–19]

Table 1. *Cont.*

Advanced Technologies	*Description*	*ESG Dimension*	*Ref.*
Additive Manufacturing (AM)	The small-batch production of customized and lighter products, also reducing logistics costs and stocks	Environmental	[20]
Augmented Reality (AR)	Improving work and maintenance procedures and promoting virtual training, in addition to various applications	Environmental	[21]
Big Data and Analytics	The collection and analysis of large data sets from different sources, supporting real-time decisions	Governance	[22]
Interconnected City logistics (ICL)	Solution toward the more-sustainable transportation of PI containers within cities	Environmental	[20–24]
Physical Internet (PI)	Virtual reality models for simulating processes	Governance	[25–27]

According to [5], the critical direction of information support of logistics activity is the integration of information flows and telecommunication development. The unified information space is vital for state-of-the-art technologies because it provides new opportunities to accommodate the increasing requirements of the demand-driven market for sustainable solutions. It might be efficient time management, defining a suitable operational model to accommodate transport flow, generating digital twins, different imitation tools, etc. The authors of [28] highlight that nodes of logistics networks are also under severe pressure to implement information technologies. For example, at the stage of transportation modeling, it is proposed to use a digital footprint method. On the basis of research conducted in [28–38], we have classified smart solutions according to their implementation of the ESG goals.

2.1. *Practical Aspects of Digitalization in City Logistics*

Specialists claim [19,27] that city logistics belongs to the supply-chain-management process, accompanying transportation and logistics in urban areas. The special features of modern city logistics are dictated by the anticipation of on-demand delivery and by flexibility supported by an omnichannel environment [3]. However, it was not always so. The digitalization of city logistics has contingently passed through several stages. The initial stage of digital transformation can be characterized by online data accessibility. During the next development phase, websites related to the analyzed area become more informative and user-friendly, and contactless payments appear. The next step is the interactive and coordinated implementation of digital systems (forming DESs [8,16]). Intelligent city logistics implies full automation, the integration of modes of transport, freely distributed information in real time, technologies for monitoring infrastructure, and cognitive technologies (see Figure 2).

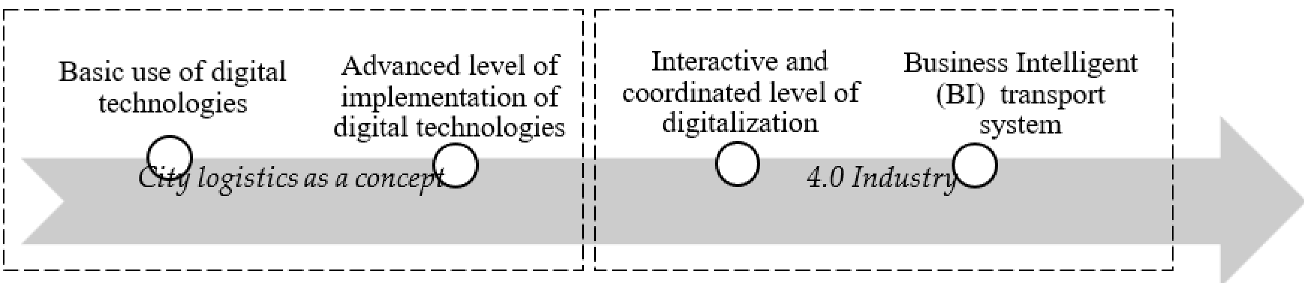

Figure 2. Evolutionary development of smart city logistics (the authors' view).

At the beginning of the article, we mentioned Japan as the first country to implement ideas of Industry 5.0. It is important to mention other countries/regions that are actively involved in increasing the digital level of society, among them the European Union. Technologies are the most crucial part of their contribution to sustainable development according to the ESG goals.

Robomobiles, or autonomous vehicles, as an element of urban transport, minimize accidents and almost eliminate human casualties. These factors lead to a significant reduction in transportation costs (savings made on fuel and workforce wages). Obtaining these advantages becomes possible because the application of the technology requires (1) stereo cameras that calculate the distance to the nearest objects; (2) cameras that identify people, vehicles, barriers, signs, and markings on the road; (3) light detection and ranging (LIDAR), which creates a 3D map; and (4) sensors and radars.

According to R&M (https://www.researchandmarkets.com, accessed on 30 June 2022), the autonomous vehicles market will comprise about 20.3 million units by the end of 2021. The rapid development of connected vehicle technologies and dynamic mobility applications and the increasing demand for safety and service are supported by the enlargement of autonomous vehicles in urban territories.

The European market of autonomous cars is actively developing. The first step for introducing such a technology into European urban logistics was taken in Germany, France, and the REAL project (Rouen Normandy Autonomous Lab, 2017–2019). Swedish startup Einride has designed a line of autonomous trucks.

Drones are also actively used in the transport system of cities in Europe and in the rest of the world. The company Dynamics, the developer and operator of cargo using uncrewed aerial vehicles, and the German logistics company Hellmann Worldwide Logistics became partners in developing a new transport service for the transportation of urgent goods. Because the regulatory framework in Europe allows the use of drones throughout its territory, this region has acted as the first zone for implementing a new service. It is planned that the first commercial flights of cargo drones will be carried out in late 2022–early 2023. Moreover, the German company Wingcopter in 2021 has developed a new autonomous aircraft to simultaneously transport three small cargo loads. The maximum speed of such a device is 150 km/h, while its maximum payload is 6 kg. On a single battery charge, the drone can cover a distance of 75 km, flying around all obstacles and delivering parcels to the right place. According to the study results, the McKinsey consulting company concluded that in the future, drones and other uncrewed vehicles would deliver up to 80% of all parcels.

To summarize the cases of several leading businesses, we have crafted a table with their various cutting-edge technologies (Table 2).

As we can see from Table 2, the performance efficiency increase might be achieved by applying information tools in line with ESG principles. Digital tools are supply-chain-management instruments and build a basis for decision-making.

Greening city logistics technologies lead to the development of modern assistance systems and special vehicles with low emissions [39,40]. For the last amendments to the ESG concept approach, it is important to mention that some authors claim that there is a transition from ESG to DESG (digital ESG) concepts [40–44]. As intelligent corporate internal control systems are becoming a part of ESG, the digitalization process is described under sustainability restrictions with DESG concepts. At the same time, research papers [39] attribute the existing shortcomings of approaches to the proper correlation between ESG concepts and social innovativeness. It is mentioned that customer perceptions should be weighted more heavily. All these issues lead to sustainable development with reasonable resource consumption and social prosperity. Importantly, such a complicated process needs a sound efficiency assessment system. There are many research studies that have been devoted to this issue. Further, the proposed methodology can be divided into three groups: analytical, empirical, and combined models. The first group of methods tends to be more interesting because it allows fir acquiring quantitative estimations and augmented conclusions. For example, in [41], the TOPSIS (technique for order of preference by similarity to ideal solution) method is used to estimate the efficiency rating of smart cities and apply sharing economy technologies with an accent on the social aspect. Despite the analytical basis of the proposed methodological approach, there are still some discussion points concerning database design for efficiency assessment. At the same time, research based exclusively on empirical methods, including KPI system design, such as [42] with further statistic processing, look comprehensive as they combine qualitative and quantitative approaches. Partly, the same methodological approach toward assessing performance indicators related to corporate social responsibility and consumer satisfaction ratings is presented in [43]; indicators previously collected as empirical grades are then analyzed with static and dynamic models. Importantly, in most cases, the indicators are detailed to a significant level [42–44]. In the context of achieving the ESG goals, more-complicated performance indicators and complex systems are considered to be of higher research interest. For example, indicators proposed in [45], namely internal resources (IR), firm performance (FP), and external environmental factor (EEF), are general and comprehensive enough to reflect the significant correlation between the social, environmental, and economic dimensions during the digitalization of modern society. In our research, we propose to use the following criteria for assessing the efficiency of implementing digital tools (Table 3), which might be aggregated into more-general KPIs and assessment systems.

Table 2. Examples of digital solutions applied by leading companies toward efficient logistics (the authors' view).

Company	Digital Technology	Comments
Amazon	1. Big data 2. Patent 11452230: 'Rack-mountable shippable network-attached computing device' 3. Patent 11451477: 'Load balanced access to distributed end points'	1. A network-attachable rack-mountable computing device, housed within a shippable enclosure, configured to mount in a rack, and applied in the multiechelon supply chain, where contractors deliver cargo. 2. A system and method for end point selection in a global accelerator system.
Transmetrics	Software solutions: NetMetric (increasing the efficiency of cargo loading) AssetMetrics (assets management) WareMetrics (optimization of a warehouse work)	The project aims to increase the efficiency of using the existing capacities and decrease the negative effects on the environment.
DHL	DHL Resilience 360: an innovation platform for risk management	Solutions on cybersecurity; supply chain visualization; an accident-monitoring system; and supply and risk control.
Evalog	City logistics solutions	Efficiency assessments of solutions are aimed at different stakeholder categories with complex criteria, including sustainability.

Table 3. Efficiency assessment criteria for implementing digital tools in city logistics toward achieving ESG goals (suggested by the authors).

Innovations and Digital Technologies	
Description	**Criteria of Efficiency Assessment**
Big data	Forecasts accuracy
Internet of Things	Business process integration level
Ecommerce	Transaction speed
Cloud logistics	Service availability
Blockchain technologies	Information flow reliability
Cybersecurity tools	Resilience level
Augmented reality	Agility

The fundamental analysis conducted for the abovementioned criteria (Table 3) allows for improving performance indicators in logistics, as sometimes companies face the challenge of nonpayback technologies. That may occur when a thorough analysis was not conducted and whena plan was not designed to achieve financial, social, or other benefits before implementing a certain digital solution. The importance of a precise analysis is emphasized in [22,46]. These authors mention that innovations should be assessed along two dimensions: operating performance (e.g., the impact of innovation investment on profits, productivity, and growth rates) and market value (the influence of innovation input on stock return or stock price). The discussion point, however, refers to the correlation between these assessment directions and the social and environmental aspects that must be considered under sustainable development goals. The subtle difference between the terms *control* and *assessment* must also be considered in the literature overview. We reckon that the first notion has a broader application field and includes an assessment process. In [44], the assessment of performance indicators is referred to as monitoring and is considered part of BPM (business process management).

In summary, digitalization, as a very complex process, must be supported by the most modern and proactive of management tools [47], including planning, controlling, and cyber-validating systems. From that point of view, the road map of digitalizing city logistics toward sustainable development under ESG principles has to imply the following sequences (Figure 3):

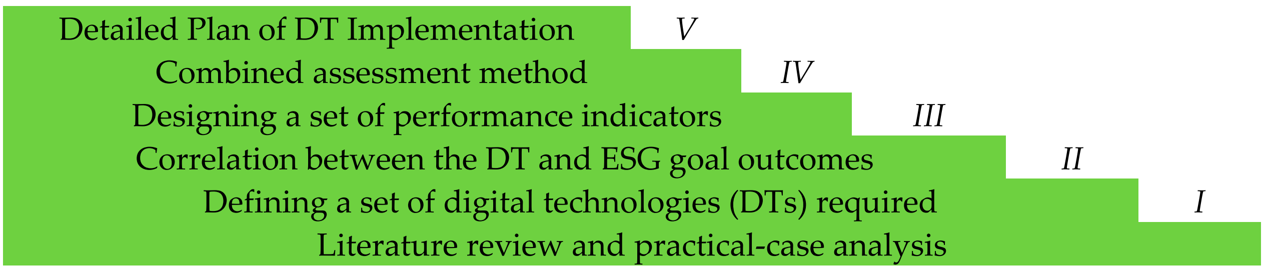

Figure 3. Road map of digitalizing city logistics under ESG principles (developed by the authors).

As shown in Figure 3, a precise analysis of the literature and practical cases should precede the second stage of defining those digital technologies planned for implementation. The next point arises out of the research gap of this study and reflects the contribution made by IT along the ESG dimensions. In the fourth stage, the focus is on management tools; among them, we highlight the efficiency assessment process as being of higher importance toward the efficient implementation of digitalization in the last step.

Thus, we suggest that digital logistics should imply modeling to achieve the multidimensional goals of the ESG concepts, apart from the controlling and monitoring systems.

The literature overview conducted on the most relevant sources has shown that despite a significant scientific background on the issue of digitalization, the ESG principles, and sustainable development, some aspects are still being discussed. Among them are the contribution of digital tools to achieving the ESG goals, the correlation between the sustainable development of cities and IT implementation, the system approach to digitalization evaluation, and some others mentioned in Section 2 of our article. These points highlight the high relevance of research conducted on practical and scientific applications.

3. Materials and Methods

3.1. Research Theory and Methodology

The constantly changing economic environment forces modern businesses to extensively apply IT. Companies focusing on implementing digital tools in their business operations benefit more than their competitors. There are many examples of companies that have refocused on IT with strong management support: KAMAZ PJSC (Russia) introduced a sophisticated monitoring and control system by establishing a particular digital transformation center, Fiat (Italy) declared the creation of smart cars in their digital platform, and so on. The digital transformation of operation management brings significant benefits to a business. That is why further investigations into the contribution of digital tools to fields other than business activity have looked promising, from applied and scientific perspectives.

With Industry 4.0's rapid development, leading companies are shifting to another type of competition. According to [5], the modern economy and state-of-the-art logistics technologies are sequenced by the last stage of Industry 4.0 development, which is referred to as hyperphysical systems. So, the central driving role figures as digital technologies' dramatically changing our lives [5–7]. Thus, digital and telecommunication technologies (such as IoT (Internet of Things), big data, cloud logistics, anticipatory logistics, online platforms, cybersecurity, and virtual reality [8–11]), smart solutions (in management, physical distribution, inventory control, etc. [10,12]), and digital society (smart city logistics, information management, machine learning, business intelligence [13–15]) are shaping a principally new way of doing business and of developing societies. All the processes pretending to be efficient are impossible to imagine outside of digitalization. Collins English Dictionary defines digitalization as converting data to a computing format (https://www.collinsdictionary.com, access date 17 September 2022). As there are many attitudes toward defining certain digitalization terms and trends, we propose applying a conceptual logic of scientific research to systemize the existing approaches (Figure 4).

At the first step of the proposed algorithm (Figure 4), the broader view of the research object is designed. Next, we suggest conducting a database search with keywords or by subject. Those papers that do not satisfy this requirement are executed without further investigation. After building a conceptual framework of sources, we continue a more-detailed search that is based on attributes. The most relevant ones are taken for the research paper literature review; the rest of the sources are considered for further investigation and will be mentioned in the discussion section. The designed algorithm is essential in terms of the research object because different digital tools and information technologies might be successfully applied to almost any sphere of society. The overview of different technologies and approaches presented in [4,5,7,8,16] and others allows us to conclude that optimization procedures based on digitalization are not restricted only by manufacturing or media. Thus, the previous systematization of different digital tools before the initial research looks relevant to obtaining detailed research results.

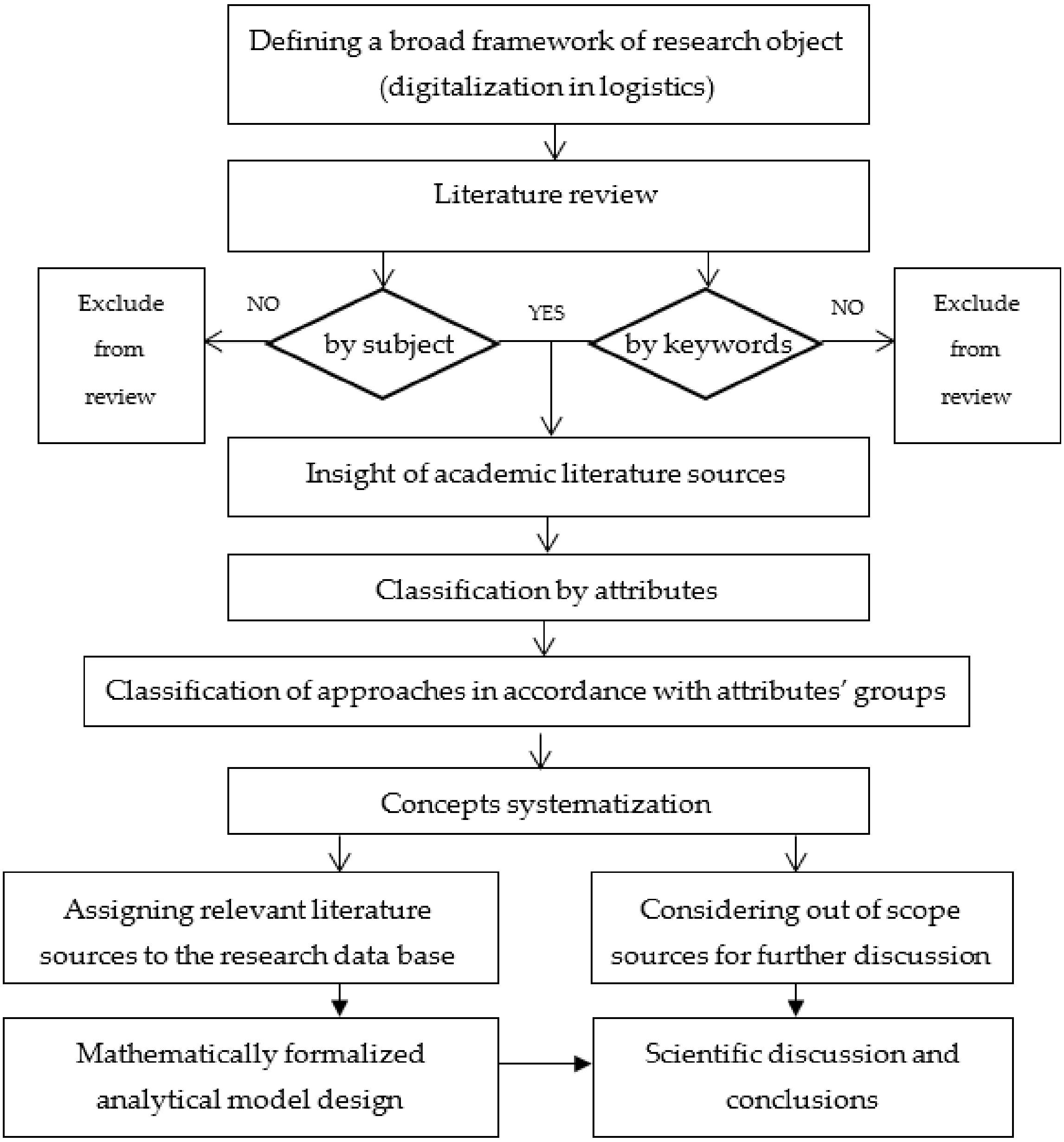

Figure 4. Algorithm of the scientific research logic for systemizing conceptual approaches (developed by the authors).

3.2. Holistic View on the Research Topic Allowing the Development of an Integrated Approach

Building a conceptual base for the research should be focused first on a precise analysis of the existing research papers devoted to the topic. Many studies are relevant to the research topic: integrated logistics, smart logistics, city logistics, digital logistics, industrial digital ecosystems, omnichannel logistics, Industry 4.0, etc. Very often, the difference between the terms remains opaque. Research papers have been taken from the past 3 years to compile a database of sources for the current research. Such an approach allows for making the obtained conclusions explicit and unambiguous. Following the logic for scientific research proposed in Section 2.1, after crafting the framework of the research object, let us systemize the concepts and define the difference between the basic terms: smart logistics, digital logistics, omnichannel logistics, and 4.0 logistics. Figure 5 presents the authors' view of the correlation and dependencies between the terms and their contributions to the research topic.

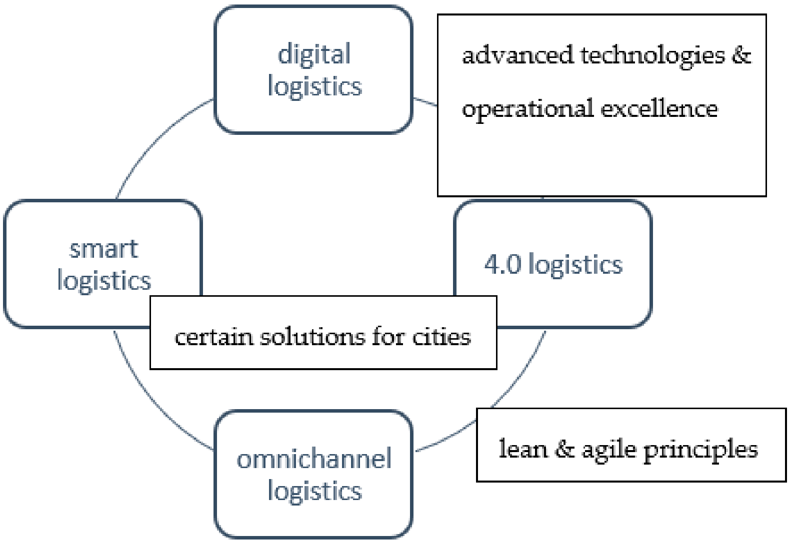

Figure 5. A holistic view on topics designing a conceptual base for the research (developed by the authors).

Supply chain management requires modern approaches and methods for planning, controlling, assessing, and forecasting, following the different concepts presented in Figure 5. All these processes are eligible for implementing digital tools and quantitative methods. A broad literature overview has shown that certain attempts have been made toward finding quantitative links between logistics, digitalization, and sustainable development. For example, [17] proposes 31 quantitative indicators to describe the correlation between social sustainability and supply chain performance. At the same time, the initial list of indicators counts more than 100 of them. Such a detailed approach to the assessment process tends to heavily consume resources. That restricts its intensive application in practice. Research proposing a qualitative assessment of ESG performance for the transport industry (port hubs in particular) is presented in the study through the performance scoring method [18]. Another attempt at quantitating the planning and analysis of logistics is proposed in [8,16], where complex information systems within the urban territory are referred to as industrial digital ecosystems (DESs). Critical supply-chain-management solutions, such as the prediction of the deviations between actual and scheduled delivery times, forecasting of shortages, inventory management, etc., are virtually orchestrated. Let us next systemize the most generalized descriptions into less-opaque definitions of the concepts mentioned in Figure 5.

Smart Logistics. Smart technologies are rapidly penetrating all spheres of our lives: smart homes, smart healthcare, smart cities, smart manufacturing, and others create a new type of people: smart consumers. The holistic approach to people and machines provides a holistic view of their coherent development. In [19,20], the authors have noted that smart logistics today means focusing on implementing informational technologies for accurate resource planning, efficient information exchange, and agility in customer service. Smart logistics is equal to last-mile delivery. The authors also mention another term referred to in smart logistics: elogistics. Virtual tools and models represent only the latter, though. Smart contracts and blockchain technologies build a supply-chain-management framework, according to [21]. However, within the mentioned technology, there is no direct reference to the term *smart logistics*.

Digital Logistics. Digitalization is characterized by active innovation involvement in all activities worldwide. Referred to as the knowledge economy [22], the digitalization of economics as a trend covers all logistics activities from planning and scheduling to physical distribution management. A more-coherent and broader view is presented in [23], where the digital logistics network is inspected, and it emphasizes the comprehensive and integral nature of all the elements included in the logistics network derived under globalization. The digital transformation of modern markets brings extra requirements to logistics networks, including the active implementation of digital tools and simulation models based on the digital twin's approach [11], where smart solutions are considered as vital drivers enabling the digital economy [14].

Omnichannel Logistics. The special role of the omnichannel concept was brought about during the pandemic of COVID-19 [23]. Alternative options for goods distribution brought growth to struggling consumer markets. Very often, focus is placed on taking a lean approach to all activities within the supply chain. For example, order picking based on lean scheduling in retail may significantly benefit overall supply chain performance [24]. The broader view of omnichannel logistics within a multiechelon distribution network and a combined framework with ecommerce logistics is presented in [25].

4.0 Logistics. According to [26], digital shadows include all the operations within the supply chain carrying out the priorities of the Industry 4.0 program. The active introduction of IT also changes modern manufacturing systems by transforming them into flexible ones [27]. Logistics within Industry 4.0 is focused on advanced production solutions, big data, cloud logistics, additive production, augmented reality, simulation models, artificial intelligence, the Internet of Things, cybersecurity, data analytics, and others [8,11,20,28,29]. Consequently, 4.0 logistics is considered a part of Industry 4.0 and might be improved such that it becomes a fully autonomous process. In [9], the authors introduce the definition of supply chain 4.0, focusing on the high impact caused by the quality of logistics infrastructure on service-oriented digital architecture and demand-driven markets. Although the concept of Industry 4.0 is still under development, most proactive researchers [31,32] mention a modified version of it: Industry 5.0, which focuses on human beings and advanced technologies at the top of society.

Some authors have already taken the opportunity to correlate smart techniques with sustainable development under Industry 4.0 [12]. They focus on lean and agile concepts toward sustainability. Operational excellence and a designed structural model for its realization as a tool for sustainable development and Industry 4.0 adoption were already being considered in 2022 in [33]. Nowadays, more and more researchers are claiming the ultimate role of humanization toward sustainable development. As mentioned in [33], 'logistics processes in customer service at the last-mile stage should be sought as a consequence of the concept of sustainable development in the socio-economic structures of enterprises. Obviously, this approach directly correlates with one of the basic ESG principles—"social"'. At the same time, we believe that a high level of integration is possible only by implementing digital tools, even if we talk about human aspects. Moreover, digital tools for achieving ESG goals aiming at sustainable development should be universal, less time-consuming, transparent, and agile. In such a case, the practical importance of the proposed methodology significantly increases.

4. Results: Smart City Logistics Model

One approach for combining the ESG concept with city logistics of smart cities is presented in [26]. Here, the mathematical game theory is applied to design different options for reducing negative externalities. Multidimensionality is typical for smart city logistics. First of all, it reflects the assortment matrix of megapolises' demands. Additionally, seasonable fluctuations must be considered because they influence social beings and city population needs.

We have developed a corresponding algorithm that includes the concerned factors. Its implementation is coherent with the digital logistics platform of a smart city and is augmented with a correlation interface with global software support for the administrative governance of a particular territory. It will contribute to a more-complete implementation of the ESG principles.

The diversity and multidimensional nature of city service structures must be considered when developing the algorithmic base for smart city logistics platforms. Further, the task is divided to several modules. The correlation between them is happening on the surfaces of interconnections between digital information flows. The coordination of informational and material flows is conducted following the time duration of transporting any goods and cargoes to megapolises [37]. It means that we include the transport city throughput into our consideration. Next, we consider the multidimensional structure of flows between the hubs of this network. To achieve a holistic view of the solutions via the ESG prism, we must supplement the mathematical model with an assessment of emerging negative externalities. It is not possible to use only the performance indicators of revenue or minimum costs when designing decision-making criteria. It is necessary to supplement them with indicators of ecological loss because they best correspond to the ESG principles [47–49].

In our research paper, we use the principles of joint formalisms presented in the differential-difference system, reflecting the transfer of material objects within a functional space. The proposed approach's scientific novelty consists in its considering a carrier to be a network-like area corresponding to the topology of the transport routes of a smart city. This critical facet is included in the parameters of digital correlation with features of the considered territory [27].

When designing a module correlating to the digital twin of the flow transfer of the multidimensional topology materials, the solutions need to be based on algorithms, and such a design had already been started in [17,34]. To do so, consider transport network representation as in the geometric graph Γ. Flows are modeled on network-like areas containing sets of correlating data on the actual topology of boundary $\partial\Gamma$ and internal $J(\Gamma)$ hubs. Thus, the correlation between the whole range of practical applications disseminators of material flow on this network might be seen, where Γ is the transport network and $\partial\Gamma$ and $J(\Gamma)$ are the boundary and the hubs, respectively. Next, the transfer processes are described by the following sequences:

$$\frac{\partial y(x,t)}{\partial t} - \frac{\partial}{\partial x}\left(ax)\frac{\partial y(x,t)}{\partial x}\right) + b(x)y(x,t) = f(x,t),$$

$$y\big|_{t=0} = \varphi(x),\ x \in \Gamma,\ y\big|_{x\in\partial\Gamma_T} = 0,$$

Here, as assumed in analogical research, the parameters $\hat{\omega} = \bigcup_{j=1}^{M} \omega_j$ и $\hat{\Im} = \bigcup_{k=1}^{N} \Im_k$ characterize the quantitative indicators of the flow condition $y(x,t)$, and function $\varphi(x)$ and $f(x,t)$ define the external properties of the transport carrier. Correlations $u(k) := u(x;k)$, $f_\tau(k) := f_\tau(x;k) = \frac{1}{\tau}\int\limits_{(k-1)\tau}^{k\tau} f(x,t)dt$, $k = 1,2,\ldots,K$, $\tau = \frac{T}{K}$. Note that in this system, functions $u(k)$ and $k = 1,2,\ldots,K$ present a discrete-time analog for the function $y(x,t)$, which is applicable for all the values $t = k\tau$, $k = 1,2,\ldots,K$.

The task of searching for a solution in a digital twin system is sequenced to solve the initial-edge task for differential sequences of the type (1). Here, we have a system of distributed parameters corresponding to a real transfer process. The advantage of this is that it provides an abstraction of a particular flow context. The solution might be defined by applying the reduction task to the following system:

$$\frac{1}{\tau}(u(k) - u(k-1)) - \frac{d}{dx}\left(a(x)\frac{du(k)}{dx}\right) + b(x)u(k) = f_\tau(k), \quad k = 1,2,\ldots,K,$$

$$u(0) = \varphi(x),\ u(k)|_{x\in\partial\Gamma} = 0,$$

We apply the semidiscrete method proposed by Erich Rothe for the time variable. The application of the Rothe principle allows for precisely designing a new class of digital twins, not only for the material flow transfer process in real time but also for modeling their dynamics in a discrete-time interpretation, which more correctly represents the essence of the economic data.

The application of the algorithmic base of the program module for smart city systems allows for achieving some critical goals. The estimated assessments give the developers and users of this solution the opportunity not only to definitively solve the differentially-difference system but to acquire the conditions of continuity from the initial database and analyze the resistance to disruption caused by the uncertainty of the external environment inherent in a smart city as an economic entity.

Moreover, reducing the differential system to a differential-difference one makes it possible to transfer the analytical results of optimal governance acquired for the differential-difference system to the tasks of optimal governance for the differential system. The consequences of such optimization are important in the economic aspect and ecological tasks related to the ESG principles. The usage of the proposed mathematical formalizations is especially efficient for developing whole classes of digitalization algorithms for networked logistics and commercial structures.

The next module of the program, an algorithmic basis for a smart city, is proposed to create a system that correctly reflects the economic genesis process as a part of the daily activities of service-providing agents who consume resources. As the simple applications of the mass theory do not allow for directly solving the task, we propose using a dynamic algorithm for the seasonality of cycles affecting the usage of logistics nodes throughout the controlled territory. At the same time, it is necessary to completely move away from productivity performance assessments on the maximum volume of flow intensity, because they lead to unreasonable expenses and investment in smart city infrastructure. Algorithm modeling is a consequence of designing the functions of dynamic flow density $\lambda(t)$. Here is a mathematical basis for one node completely scalable on the whole transport network. In practical tasks, the range of change $\lambda(t)$ from maximum to minimum may acquire significant values, demonstrating the inadmissibility of operating with averaged values. It is also necessary to adjust the throughput $\nu(t)$ with proactive and dynamic coordination $\lambda(t)$. For this, data flow processing $\lambda(t)$ is conducted to apply mathematical modeling based on correlation between the analogs of the Erlang systems. At the same time, we take into account the random nature of logistic requests and describe the parameters of their probability for the time interval from t till $t+h$ by summing them: $\lambda(t)\ h + o(h)$. This approach considers function dependence $\lambda(t)$ only on time t, and the system state does not influence it. Next, the probability of conducting logistics operations at a time interval from t till $t+h$ is defined as $\nu(t)\ h + o(h)$. This will make it possible to compose a system of differential equations based on periodic $\lambda(t)$ and $\nu(t)$ with the same values of the whole period T. As a result, we formalize the desired probabilities of the system state $E_k(t)$ by combining them: $p_k(t) = \pi_k(t) + \alpha_k(t)$. Correlation functions $\pi_k(t)$ and T are periodical and satisfy the following condition: $\lim\limits_{t\to\infty} \alpha_k(t) = 0$ for all possible k. Functions $\pi_k(t)$ correlate to the stationary probabilities of states; that is, dynamic dependencies target $p_k(t)$, the daily activity of a smart city logistics hub.

It immediately gives such parameters, as stated, working hours and the periodicity of indicators: query lengths on completing functions and operations, and the distribution function of time costs on the completion of logistics activities.

The basis of the mathematical models produces the following set of equations:

$$p'_0(t) = -\lambda(t)p_0(t) + \nu(t)p_1(t)$$

$$p'_1(t) = -\nu(t)p_1(t) + \lambda(t)p_0(t)$$

As performed: $\sum\limits_i p_i(t) = 1$ Or:

$$p_0(t) + p_1(t) = 1$$

Possible to transform to the following view:

$$p'_0(t) = -(\lambda(t) + \nu(t))p_0(t) + \nu(t)$$

For calculations, there are initial conditions needed: $p_0(0) = \alpha \leq 1$, $p_1(0) = 1 - \alpha \leq 1$. As a result, it becomes possible to apply the described analytical solution by using the following equations:

$$p_0(t) = e^{-\int_0^t [\lambda(x)+\nu(x)]dx} \left[\alpha + \int_0^t \nu(x) e^{-\int_0^x [\lambda(z)+\nu(z)]dz} dx \right]$$

Next, by applying the periodic attributes $\lambda(t)$ and $\nu(t)$, it is possible to define the function $\varphi(t)$ through the following sequence:

$$\varphi(t) = \int_0^t [\lambda(x) + \nu(x)]\, dx$$

Add the system with the parameter k, corresponding to the inequity $kT \leq t < (k+1)T$, and consider periodical values $\lambda(t)$ and $\nu(t)$ to transform the given task into the following:

$$\varphi(t) = \sum_{l=1}^{k} \int_{(l-1)T}^{lT} [\lambda(z) + \nu(z)]dz + \int_{kT}^{t} [\lambda(z) + \nu(z)]dz$$

It might be simplified by introducing additional variables:

$$\varphi(t) = ka + \int_0^{\tau} [\lambda(z) + \nu(z)]dz$$

Consequently,

$$a = \int_0^T [\lambda(x) + \nu(x)]\, dx,\ \tau = t - kT$$

In the same way, consider the second sequence:

$$\int_0^t \nu(x) e^{\varphi(x)} dx = \sum_{l=1}^{k} \int_{(l-1)T}^{lT} \nu(x) e^{\varphi(x)} dx + \int_{kT}^{t} \nu(x) e^{\varphi(x)} dx$$

Accordingly, for $b = \int_0^T \nu(x) e^{\varphi(x)} dx$, the probability is calculated by using the following equation:

$$p_0(t) = e^{-\varphi(\tau)} \left[\frac{b}{e^a - 1} + \int_0^{\tau} \nu(x) e^{\varphi(x)} dx \right] + e^{-ka-\varphi(\tau)} \left[\alpha - \frac{b}{e^a - 1} \right]$$

An analysis of the expression demonstrates that the first term of it is a periodical function of the time argument t and is also invariant to the initial conditions. The second term of the expression converges to the steady state and increases time $t \to \infty$ targeting to zero. It brings an important result, sequenced in the mathematical modeling of complex correlations, on designing material flows such that they reflect smart city activity.

The set of mathematical modeling equations allows for solving the task of dividing complex seasonal correlations into a set of periodical variables. The designed approach applies to using the Fourier decomposition method for the numerical representation of random periodical processes.

For smart city tasks, let us define the planning horizon with the period T_{Σ}; in the most widespread case, it is equal to the calendar year. However, to generalize the results, we consider multiple random values. Thus, we apply harmonic division to present $X(t)$ hubs as follows:

$$M[X(t)] = M_0 + \sum_{k=1}^{\infty} \mu_k \cos(k \cdot \omega t) + \nu_k \sin(k \cdot \omega t) \text{ where } \omega = 2\pi / T_{\Sigma}$$

where coefficients M_0, μ_k, and ν_k are defined according to the aforementioned equations. Thus, we acquire a mathematical model of the performance of smart city logistics hubs that is applicable to programming and numerical methods. The input parameters are presented by a data flow of intermachine correlations of smart city systems.

Additionally, the proposed mathematical model also provides an algorithmic basis for modeling smart city systems with losses. This is possible by satisfying the following:

$$\nu(t) > 0, \int_0^{\infty} \nu(x)dx = \infty$$

On any ended t, $\int_0^{t} \nu(x)dx < \infty$. Practical applications of solving these tasks are essential for the ecological dimension of the ESG principles.

In planning current economic activity, smart city administrators must focus on the indicator system in a way that is highly different from focusing on commercial business criteria. The tasks of smart city governance are supplemented with quality-of-life, ecological, and other special indicators.

In our opinion, the distribution of the limited budgeting has to be performed simultaneously in the majority of directions, which suggests balancing the definition with ESG principles when applying the algorithm of designed mathematical modeling.

Consider some investment directions connected with ecology, quality of life, and infrastructure development to all city service branches, the number of which varies according to the territory. For scaling the solution, let us define their number as s. On investing the budget volume v_j to ecological programs in a branch number j, for $j = 1, 2, \ldots, s$, the resulting effect is assessed with a function $P_j(v_j)$. The same is true for investment in a volume w_j on quality of life, where we obtain the correlation $Q_j(w_j)$ on investment in infrastructure object $R_j(x_j)$.

Consider the existing limitations L_j on assigning directions $j = 1, 2, \ldots, s$ and N, which is the total budget volume in the administration of smart city governance.

Here, the programming module has the same algorithmic structure. The optimal volume search is necessary $P_j(v_j)$, $Q_j(w_j)$, $R_j(x_j)$ for all $j = 1, 2, \ldots, s$, according to the maximization-of-quality criterion:

$$\sum_{j=1}^{s} \left[P_j(v_j) + Q_j(w_j) + R_j(x_j) \right]$$

According to these conditions, restrictions allow us to add the following inequalities of completing a task:

$\sum_{j=1}^{s} (v_j + w_j + x_j) \leq N$ and $(v_j + w_j + x_j) \leq L_j$ $j = 1, 2, \ldots, s$. In addition, given the nature of the variables, it is necessary to satisfy the following conditions:

$$v_j \geq 0\,, w_j \geq 0\,, x_j \geq 0 \text{ for } j = 1, 2, \ldots, s$$

The solution algorithm is designed for discrete optimization. In this case, the recurrence relation is as follows:

$$g_j(n) = \max\left[P_j(v_j) + Q_j(w_j) + R_j(x_j) + g_{j-1}(n - v_j - w_j - x_j)\right]$$

for $j = 1, 2, \ldots, s$.

This allows us to design a searching process with a dynamic programming method, where additional $g_j(n)$ represents the maximum search regarding estimated interactions and n represents the current estimated volume of distributed funds from the raw $n = 0, 1, 2, \ldots., N$. Accordingly, the following inequality condition is checked:

$$(v_j + w_j + x_j) \leq \min(L_j, n)$$

The advantage of the proposed methodology comes from not only its algorithm scaling but also its ability to apply to a wide spectrum of problems arising from smart city performance. Most of the indicators in such economic entities have a seasonal nature. The application of the proposed algorithms allows for formalizing their parameters, and the explicit nonlinear trend of functional sequences and limitations are included in numerous diversified program applications.

In conclusion, it is essential to mention that the presented modules build an algorithmic framework for expert decision-making on the smart city concept. Further, argument sets serve as interfaces providing digital data on the intermachine correlation regime M2M.

Discussion

The authors could contend that the suggested approach presents a way of achieving strategic ESG goals by applying digital technologies at smart city logistics. The researchers suggest considering the implementation of digital logistics in ESG goals without other industrial engineering and management activities, such as smart manufacturing, extended customer service, alternative delivery routes and options, and return flow management. The researchers consider that the prerequisites of the developed approach emerged from the idea of sustainable development of the world's economy with a further focus on city logistics issues. At the same time, the proposed methodological approach for mathematical modeling assumes some reconfiguration toward considering generalizations that can be made of these systems. For example, the researchers may use some improvement by introducing new variables and limits for applying the proposed mathematical model at the level of a region, a country, or a country union. So, smart cities, as the object of study, are supposed to be the first conceptual step toward further methodological development. Herein, the authors propose smart city modeling on the example of a transportation node, not a whole smart city logistics system, by assuming the standard features of the system (smart city) and its nodes (transportation hub). The objective functions of some nods may differ from the whole aim of the system. For example, zero-emission transportation takes more time, targeting emission reduction; at the same time, the entire system might be targeting a logistics cycle speed increase and a total delivery time reduction. So, considering particular cases such as the mentioned one is a future direction for future research.

The research paper considers both definitions of basic terms related to smart city logistics and interaction interfaces within the optimal discrete mathematical model. The article provides a theoretical description of business processes within smart city logistics, including planning and performance assessment. The results are primarily academic and provide mathematical models, suggesting their potential application. The possible research areas could be based on the concept of digital twins and the digitalization of logistics business processes [26,37,48].

The authors propose to discuss the possibilities of applying the developed approach in the context of sustainable development [17,34] and digital ecosystems [8,16], as well as taking into account the changes in various conditions of the functioning of logistics networks under the influence of certain factors [34–36]. Further investigations in this direction will help obtain advanced models for particular cases.

5. Conclusions

The application of digital technologies is carried out in all logistics-related operations: logistics infrastructure management, vehicle routing problems, quality management, service level maintenance, inventory control, and many others. Moreover, digitalization significantly impacts employees, working conditions, management skills, and competencies. Thus, any assessment of the impact of digital technologies on modern society should be multidimensional. On this issue, we decided to investigate the effect of digitalization on smart city logistics within the ESG principles, as environmental, social, and governing aspects are crucial for the sustainable development of modern countries. This tendency is also justified by the European Commission's goals, setting the plan for 2022 to build a more environmentally friendly and digital future. To achieve this goal, 30% of the total EU budget is introducing green technologies and at least 20% is facilitating a digital transition. In 2021, as a whole, member states allocated about 40% of their funding to combat climate change and about 26% to promote a digital transition. This fact underlines the relevance of the study topic. The purpose of the research on investigating the effect of digital technologies on smart city logistics through the ESG goals has been achieved. We distinguish the following research purposes:

- An algorithm of the scientific research logic for systemizing conceptual approaches was designed.
- A holistic view on topics designing a conceptual base for the research was proposed.
- A correlation between digital technologies in supply, manufacturing, and distribution and the ESG goals was found.
- A road map of digitalizing city logistics under ESG principles was developed.
- A mathematical model for discrete optimization, complied with additional investment and budgeting control functions in smart cities, was designed.

To sum up, we note that, on one hand, the digitalization of city logistics provides numerous opportunities, increases the level of security, accelerates the performance of monotonous operations, and solves such problems as traffic jams, pollution, a lack of choice for consumers, the inefficient utilization of vehicles and space, but on the other, risks such as increased work intensity, changes in the job profiles due to new tasks, and the need for employees to learn new skills and competencies in the field of smart city logistics should not be excluded. In this case, the effective implementation and subsequent use of digital logistics technologies require the interest and motivation of employees to learn new digital tools.

The outlined target of defining possible ways for IT to contribute to environmental, social, and governing excellence in city logistics has been achieved in our research through a multidimensional approach to case solving. We suggest that achieving high social development goals with a focus on smart solutions for city logistics is the most important field for contributing to the ESG goals. The authors have provided practical applications of the research as digital tools for developing the fundamental principles of ESG in city logistics through a mathematically formalized stochastic discrete model.

The authors' approach is based on the idea that businesses and social governing administrations are looking for more-complex schemes, complicating the overall interaction structure between the owner of the resources and the end user. From the authors' point of view, the theoretical fundamentals for creating and developing intelligent systems toward the integration of digital tools in smart city logistics, under the constraints of the ESG goals, are based on the Industry 4.0 doctrine and provide diversified opportunities for future research.

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