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# A Decision Support Model for Lean Supply Chain Management in City Multifloor Manufacturing Clusters

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**Abstract:** City manufacturing has once again become one of the priority areas for the sustainable development of smart cities thanks to the use of a wide range of green technologies and, first of all, additive technologies. Shortening the supply chain between producers and consumers has significant effects on economic, social, and environmental dimensions. Zoning of city multifloor manufacturing (CMFM) in areas with a compact population in large cities in the form of clusters with their own city logistics nodes (CLNs) creates favorable conditions for promptly meeting the needs of citizens for goods of everyday demand and for passenger and freight transportation. City multifloor manufacturing clusters (CMFMCs) have been already studied quite a lot for their possible uses; nevertheless, an identified research gap is related to supply chain design efficiency concerning CMFMCs. Thus, the main objective of this study was to explore the possibilities of lean supply chain management (LSCM) as the integrated application of lean manufacturing (LM) approaches and I4.0 technologies for customer-centric value stream management based on eliminating all types of waste, reducing the use of natural and energy resources, and continuous improvement of processes related to logistics activities. This paper presents a decision support model for LSCM in CMFMCs, which is a mathematical deterministic model. This model justifies the minimization of the number of road transport transfers within the urban area and the amount of stock that is stored in CMFMC buildings and in CLNs, and also regulating supplier lead time. The model was verified and validated using appropriately selected test data based on the case study, which was designed as a typical CMFM manufacturing system with various parameters of CMFMCs and urban freight transport frameworks. The feasibility of using the proposed model for value stream mapping (VSM) and managing logistics processes and inventories in clusters is discussed. The findings can help decisionmakers and researchers improve the planning and management of logistics processes and inventory in clusters, even in the face of unexpected disruptions.

**Keywords:** supply chain management; sustainability; learn manufacturing; city logistics; transportation

## 1. Introduction

The placement of green smart manufacturing of consumer goods in residential areas of large cities is one of the priorities for their sustainable development [1–3]. City multifloor manufacturing clusters (CMFMCs) in large cities are organized among small and medium-sized enterprises (SMEs) located in areas of compact allocated urban population in order to meet consumer needs [2,4,5]. The personnel of such enterprises mainly live in the same area, and in the case of family enterprises—directly in the place of residence as the home of fabrication [6,7]. The proximity of the manufacturer to the consumer allows for the reduction of transportation costs and time for the delivery of products. This is especially important as transport costs comprise a significant share of the product price, including the value of transport time (depreciation costs), which is particularly visible when the necessary production materials or finished products are imported from another continent.

The orientation of consumers toward the products and services of local producers contributes not only to the reduction of regional and international cargo transportation but also has a beneficial effect on the economic and social components of the sustainable development of large cities. CMFMCs enable the streamlining of urban traffic by reducing the flow of citizens employed in production [8,9]. CMFMCs also produce products for various SMEs and entities located in large city areas [7]. CMFMCs are an alternative to the production systems commonly used in industrial areas [1,2].

Industrial companies in large cities are located outside residential areas in industrial areas called industrial and technology parks (ITPs). Industrial companies are sources of intense noise, vibrations, gas emissions, and other negative phenomena that are incompatible with the residential and historical zones of large cities [9]. A characteristic phenomenon for ITPs is the presence of intense urban traffic of public and individual transport before and after work shifts, which inevitably leads to traffic congestion, loss of personal time, and increased emissions of exhaust gases from transport vehicles [10,11]. With all this in mind, CMFMCs may constitute an important new element of the production system in agglomeration areas, positively influencing both the costs and quality of production as well as the accompanying transport and logistics systems. Although CMFMCs have been looked into quite a lot for their possible uses, very little has been done in terms of improving supply chain design efficiency concerning CMFMCs.

The supply of SMEs and other entities and the shipment of finished products to consumers in each CMFMC is carried out through its city logistics nodes (CLNs), which are usually adjacent to the appropriate shopping centers of the cluster [2]. Material flows to/from CLNs are divided into intra-cluster and extra-CMFMC, which use the appropriate urban freight transport [12]. E-vans are used inside and outside the CMFMC for transportation within the residential area of a large city, and e-trucks are used for non-cluster transportation outside the residential zone, which deliver cargo from intermodal logistics nodes (ILNs). The ILN is an transhipment and storage hub that handles cargo between long-distance transport modes and the urban transport system based on e-trucks and e-vans. The delivery of cargo to the ILN is carried out mainly by intermodal transport using intermodal transport units, mainly containers and swap bodies [12,13]. ILNs are located outside residential areas, mainly in the industrial areas or ITPs of large cities [11].

The purpose of this study is to identify the factors influencing lean supply chain management in the implementation of cargo transportation and storage for city multifloor manufacturing (CMFM) enterprises. Supplies include raw materials and semi-finished products, i.e., the materials needed for CMFM-specific production. Based on the results of this research, organizational and technical assumptions for an efficient supply chain will be identified. The two most important selection criteria were adopted, including: (1) minimizing the number of road transport transfers within the urban area, and (2) minimizing the amount of stock that is stored in CMFMC buildings and in CLNs. These two criteria appear to be opposite, which makes the specific aim of the research to find the optimal supply chain option, measured by the volume of stocks and road transfers within the CMFMC supply chain. Hence, the following research questions (RQs) can be formulated:

RQ1: What is the relationship between the number of CMFMC buildings (CMFMBs) and the number of vehicles (e-trucks and e-vans) needed, as well as the number of road transfers at two inter-city transport legs, i.e., ILN–CLN and CLN–CMFM buildings?

RQ2: What is the relationship between the number of CMFMBs and the demand for cargo storage service in the CLNs that supply these buildings?

RQ3: What is the relationship between the level of utilization of vehicle loading capacity at two inter-city transport legs and the demand for cargo storage service in CLNs and CMFMC buildings?

RQ4: What factors affect the supplier lead time calculated for any ITR transported from the ILN to the CMFMB?

The answers to the research questions posed are based on a literature review of the field of lean supply chain management for large cities and the development of a decision support model of lean supply chain management for CMFMCs in order to numerically model supplies and find the best solutions for using the transport and storage potential of all stakeholders. The case study allowed us to confirm the validity of the proposed model and identify managerial implications, gaps, and directions for future research.

The paper is organized as follows: Section 2 presents the literature review of the research on lean supply chain management for city manufacturing. Section 3 provides the materials and methods in our research. Section 4 introduces the problem definition, notation, and assumptions. A decision support model of lean supply chain management for CMFMCs, a case study, and managerial implications are elaborated in Section 5. Section 6 contains a discussion of the results obtained and available management solutions for lean supply chains for CMFMCs. Section 7 presents the conclusions and opportunities for future research.

## 2. Literature Review

### *2.1. Lean CMFM and Urban Freight Logistics*

Lean CMFM is an integrated application of approaches to organizing production within a smart, sustainable city, philosophy, the principles of lean manufacturing (LM), and the Industry 4.0 (I4.0) concept [2,14].

Smart, sustainable CMFM involves green production systems, which are located in residential areas and are focused exclusively on products for local consumers using I4.0 technologies and a sustainable three-dimensional approach to the city development, considering environmental, economic, and social aspects [9,15,16].

Reducing transport performance from manufacturers to consumers and the distance between the place of work and residence of CMFM personnel contributes to the sustainable development of the urban transport system, reducing transport costs and gas emissions [8,12]. Sustainable development of smart CMFM became possible due the emergence of green production systems and technologies, primarily additive technologies, the improvement of information and communication technologies and socio-cyber-physical systems as key components of I4.0, and a modular approach to the design of products and process equipment [7,17,18]. Among the conceptual systems and disruptive I4.0 technologies within the CMFM in urban freight logistics are the digital ecosystem, cloud-based manufacturing, supply chain and materials handling systems, artificial intelligence, digital twins, big data, cloud computing, augmented reality, radio frequency identification (RFID), 5G, Internet of Things, and blockchain, which make it possible to implement the Cloud Manufacturing-as-a-Service concept for city producers and consumers [7,16,19,20].

Lean manufacturing (LM) is Toyota production system that implements production strategies and enterprise management styles to improve the performance, competitiveness, and sustainability of its business through continuous improvement of production and logistics processes and operations, eliminating various types of waste, and increasing added cost for clients [14,21,22]. The integration of LM principles and I4.0 technologies has led to the emergence of new opportunities in the formation of value streams in enterprises that help them to achieve higher economic performance [23–25]. Recent studies have shown the significant impact of integrating I4.0 and LM practices in enhancing the ability of enterprises to achieve the goals of environmental sustainability and green production [14,26]. Thus, the application of LM principles in CMFM is a promising strategy for the development of green production in the framework of a smart, sustainable city.

LM is also a multi-faceted production approach involving a just-in-time (JIT) production as a management system aimed at eliminating production and transportation waste, due to the inefficiency and ineffectiveness of processes, and reducing inventory [27,28]. The development of I4.0 technologies promotes close relationships between suppliers and customers, which provides new opportunities for JIT production through improved communication and supply transparency [29]. JIT production involves the start of production and logistics procedures after receiving an order from the consumer for the manufacture of products with agreement on the cost, timing, and production volume. This allows production enterprises and CLNs to reduce unnecessary costs associated with excess inventory, energy, and resource consumption, respond only to real consumer demand and market trends, and plan and implement lean supply chains [30]. Reyes et al. [31] defined lean supply chains as "a set of organizations directly linked by upstream and downstream value streams between processes that work collaboratively to reduce costs and waste". It is clear that the implementation of lean supply chains depends on the effectiveness of JIT production planning and value stream management through continuous improvement of production and logistics processes and minimization of inventories [31,32]. Inventory in CMFMCs accumulate at production enterprises and in CLNs also as a result of urban logistical problems arising from timely cargo delivery to consumers. It is obvious that inventory management within JIT production in CMFMCs is interconnected with the management of urban freight transport [33,34].

Urban freight logistics is concerned with optimizing the operations required to move goods in cities [35]. The resolution of urban freight logistics problems is associated with the division of transport flows internally into CMFMCs (between CMFMBs and the CLNs), externally (between ILNs and the CLNs), and between CLNs [12]. Cargo delivery in an urban environment is implemented in intelligent reconfigurable trolleys (IRTs), which are transported in e-trucks and e-vans in the form of connected multi-IRTs [7,12,36]. The performance of urban freight logistics in a large city is associated with the lean concept of supply chain management, which is based on customer-centric operations, continuous improvement of logistics processes, and inventory reduction [33,37,38].

### *2.2. Lean Supply Chain Management in CMFMCs*

Lean supply chain management (LSCM) can be defined as the integrated application of lean manufacturing (LM) approaches and I4.0 technologies for customer-centric value stream management based on eliminating all types of waste, reducing the use of natural and energy resources, and continuous improvement of processes related to logistics activities [39,40]. The LSCM techniques are JIT production, leadership management, information technology management, supplier management, process standardization, customer relationship management, logistics management, and elimination of waste by value stream mapping (VSM) and continuous improvement [38,39,41]. Tortorella et al. [38] identified the following four key bundles of LSCM practices: "customer supplier relationship management, logistics management, elimination of waste and continuous improvement, and top management commitment".

The practical application of LSCM contributes to increasing the economic efficiency and performance of logistics operations [42,43]. LSCM performance is based on balanced scorecard (BSC) models [44] and supply chain operations reference (SCOR) models [45,46]. The balanced scorecard perspective is related to aspects such as financial, consumer, business process, learning, and growth, which have appropriate goals and key performance indicators [44]. Supply chain performance measurement models have also evolved, including performance measurements for both qualitative and quantitative aspects [44,47–50]. For example, the business process goals are waste reduction, supplier relations, and logistics process optimization, and their LSCM key performance indicators are inventory turnover ratio, productivity, defect rate, first time through, supplier delivery reliability, supplier rejection rate, and supplier lead time [44]. However, LSCM is a comprehensive approach to optimizing supply chains in CMFMCs, which covers a wider range of issues, including not only economic but also social and environmental issues, and is therefore an important aspect of sustainable development of urban manufacturing in a smart city [12,31]. Social outcomes from LSCM implementation are manifested by consumer satisfaction with the timeliness and quality of deliveries, improving the social atmosphere at CMFMC enterprises, and increasing the motivation, safety, and well-being of employees [14,31,51]. A broader approach to the social aspects of LSCM includes all stakeholders in logistics processes, whose interests are considered in decision making and valued [52]. A significant contribution from LSCM implementation to the environmental component of the sustainable development of a smart city is expressed in reducing energy consumption, waste generation, and greenhouse gas emissions by optimizing urban freight transport and reducing excess inventories [14,30,31]. It is obvious that achieving the strategic goal of sustainable development of CMFMCs within a smart city is associated with achieving a balanced scorecard of LSCM performance indicators [38,44].

A key technique of LSCM is the VSM method, which allows stakeholders to visualize, evaluate, and analyze the materials and information flows throughout the supply chain and identify opportunities to improve them and reduce excess inventory [42,53]. In this study, the VSM of supply chains in CMFMCs includes all logistics processes and operations related to the materials and information flows from providers to consumers, namely in ILN–CLN and CLN–CMFMB transport relationships. The VSM allows stakeholders to gain insight into the current flows of materials and information throughout the supply chain. Analysis of the current flows of materials and information throughout the supply chains in CMFMCs based on VSM helps to identify waste, including inefficiencies and ineffective logistics processes, and reduce excess inventory, and it is the basis for designing a future-state map of a value stream [28,42]. The future-state map of the supply chains in CMFMCs includes all improvements and, after implementation, acquires the status of the current-state map of supply chains with subsequent analysis of its performance. The process of improving supply chains based on VSM is continuous. The activation of changes in the value stream occurs only after the identification of waste in the supply chain and the availability of an effective means to eliminate it [42,53].

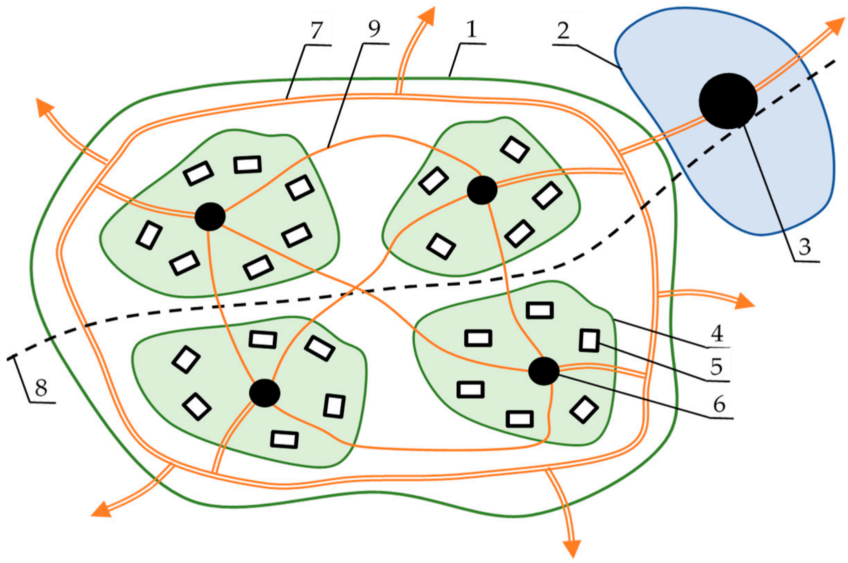
The SMEs of CMFMCs are dominated by a high level of production differentiation, with the formation of functional orientation and network organization, which are characterized by a staggered and chaotic value stream [53,54]. The staggered and chaotic production value stream also extends to the implementation of supply chains in CMFMCs. The supply chain uncertainty in CMFMCs increases the role of value stream planning and subsequent improvements to reduce the SME response time to customer demand, increasing their performance and competitiveness [53]. Planning and improvement of logistics value streams in CMFMCs is based on the analysis of waste in supply chains. Waste in CMFMC supply chains can be divided into direct and indirect. Direct waste in the supply chains in CMFMCs include the presence of redundant forward and pending buffers; long supplier lead time and waiting time for operations, including due to excess inventory, poor planning, and unauthorized movements; underutilized vehicle resources; long trip times; and excess inventory throughout the supply chain [2,42,44]. Indirect waste is the result of direct waste and is associated with overspending of natural, energy, and financial resources and other environmental and social aspects (e.g., increases in greenhouse gas emissions and environmental pollution, customer and personnel satisfaction, value, etc.) [44,53,55,56].

The presented literature review, and similar reviews made by researchers in recent years, highlight significant gaps in research on LSCM performance and its indicators, in particular, business process indicators in CMFMCs [44,50,57,58]. The development of a decision support model for LSCM is based on the creation and application of appropriate performance indicators for business processes in CMFMCs [44,53,59]. Therefore, this study aims to develop a decision support model for LSCM in CMFMCs, which focuses on identifying direct waste in supply chains and improving the stages of logistics processes in order to increase the value stream.

## 3. Materials and Methods

The development of the decision support model for LSCM in CMFMCs was based on a practically relevant context and a case study to validate it. The practically relevant context is based on examples of large European cities, such as Berlin (Germany), Amsterdam (Holland), and Lodz (Poland), which are characterized by a developed city manufacturing and freight transport infrastructure (including the city ring road). The case study is also a reliable and useful practice for identifying new concepts and research directions [20].

Figure 1 shows a large city scheme with CMFMCs, roads, and rail network for freight transport [12]. The large city is represented by residential (1) and industrial (2) areas. In the industrial area (2), along with its ITPs, there is the ILN (3), through which external intermodal supplies of raw materials, components, and goods are carried out for the production needs of the ITPs and CMFMC (4) enterprises. The CMFMCs (4) are represented by multi-floor buildings CMFMBs (5), in which production enterprises, mainly SMEs, are located. The finite production capacity of CMFMBs is defined by the throughput capacity of their freight elevators, which depends on their number, capacity, and number of building floors [2]. The CLNs (6) in the CMFMCs are a leading provider of smart sustainable logistics services, which include storage, sorting of IRTs, multi-IRTs and their cargo, and the delivery of cargo to intra-cluster and extra-cluster consumers with the ability to monitor (including visual) these operations in real time by all stakeholders [12].




1 – residential area of a large city; 2 – ITPs; 3 – ILN; 4 – CMFMCs;
5 – CMFMCBs; 6 – CLN; 7 – city ring road; 8 – railway; 9 – city roads

**Figure 1.** Scheme of a large city with CMFMCs, roads, and rail network for freight transport.

External (in relation to the large city) cargo deliveries to the ILN are carried out by intermodal freight transport using intermodal transport units. The delivery of ISO intermodal containers and swap bodies to the ILN is implemented via heavy good vehicles (HGVs) and intermodal trains from regional or sea terminals. HGVs use only external (extra city) and the city ring road (7) and railway (8) (Figure 1) without the possibility of entering the residential areas of a large city [11]. Cargo in IRT units is delivered by e-trucks between the ILN and CLNs through the city ring road (7). Within each CMFMC, cargo transfer between CLNs and CMFMBs is carried out by e-vans using city roads (9) [12].

The development of the decision support model for LSCM in CMFMCs is based on the integration material flow analysis (MFA) and VSM [30,42,47]. MFA allows for the quantification of flows, inventory, cargo inputs, and outputs of ILNs and CLNs [12,60]. The efficiency evaluation of freight vehicle use is defined by the utilization level of their loading capacity, number of e-truck and e-van transfers from ILNs to CLNs and CLNs to CMFMBs, respectively, and the stowage factor of production material loaded in ITRs [2]. The VSM method is a key aspect of LSCM, which involves identifying and visualizing materials and information flows throughout the supply chain (Figure 2) [42].

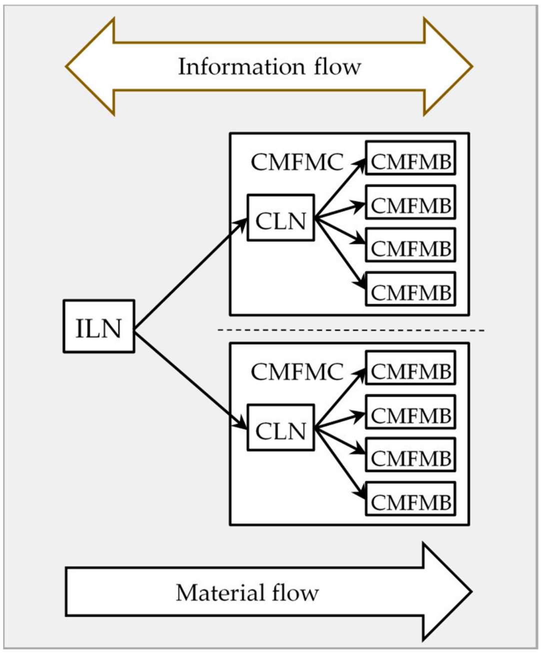



**Figure 2.** Supply chain of CMFMCs within a large city.

Figure 3 shows the stages of the LSCM continuous process based on the VCM method [51]. Improving the value stream is aimed at reducing the supplier lead time and includes the following stages: cargo selection, planning the current-state map, its analysis with subsequent improvement, and creation of a future-state map of a value stream. This allows stakeholders to analyze the current-state map of a value stream, identify areas of waste, and eliminate them in a timely manner [39,42].

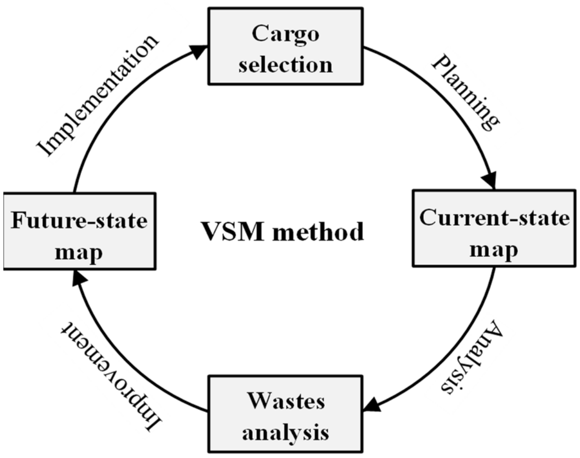



**Figure 3.** Stages of LSCM continuous process based on the VSM method.

## 4. Problem Definition, Notation, and Assumptions

### *4.1. Problem Definition*

Planning of inventories and cargo deliveries to ILNs, CLNs, and enterprises in CMFMBs is associated with solving a number of problems, among which can highlight the following: (i) formation of freight vehicle fleets of optimal capacity, taking into account the number of CMFMBs; (ii) reduction of empty runs as part of the implementation of the closed-loop economics concept; (iii) implementation of JIT deliveries to reduce inventories in CMFMCs taking into account the throughput of CLNs; and (iv) supplier lead time reduction. The solution to the identified problems is related to the design and validation of a decision support model for lean supply chain management in CMFMCs, which will allow stakeholders to find the best options for the delivery and inventory of cargo in real time.

Figure 4 presents the CMFM cluster delivery system used in this study.

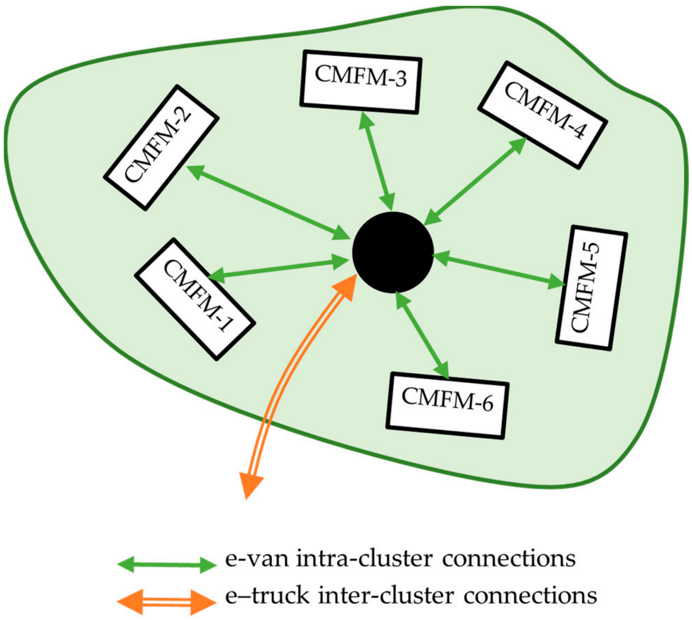



**Figure 4.** CMFM cluster delivery system.

### *4.2. Notation*

A tabular summary of all indexes and parameters used in the further part of the research is presented below (Table 1). The key parameters are related to: daily demand for production materials ($D_{md}^{CLN}$, $D_{md}^{CMFMB}$) ordered by CLNs and CMFMBs that are part of the CMFMC, the number of delivery vehicles ($M_{truck}$, $M_{van}$) and vehicle journeys each day, and the overnight stock of production materials ($Q_{md}^{CMFMB}$) in CLNs. The parameters were divided into dependent and independent, in accordance with the research assumptions adopted for this stage of the development of the computational model. An increase in the number of dependent parameters is expected in planned further studies.

**Table 1.** List of indexed and parameters.

| Index: | | Unit |
|---|---|---|
| $d$ | day $d = 1, 2, 3, \ldots 365$ | |
| $m$ | type of production material, $m = A, B, C, \ldots P$ | |
| $n$ | number of CMFMBs in CMFM cluster, $n = 1, 2, 3, \ldots, N$ | |
| Parametrs: | | |
| Independent parameters | | |
| $d_{truck}$ | distance between ILN and CLN | km |
| $d_{van}$ | distance between CLN and CMFMB | km |
| $C^{van}$ | level of utilization of e-van loading capacity (last e-van in transfer group) | %, ITR |

**Table 1.** *Cont.*

| Index: | | Unit |
|---|---|---|
| $C^{truck}$ | level of utilization of e-truck loading capacity (last e-truck in transfer group) | %, ITR |
| $R^{truck}$ | maximum cargo capacity of e-truck | ITR |
| $R^{van}$ | maximum cargo capacity of e-van | ITR |
| $SF_m$ | stowage factor of m type of production material loaded in ITR | t/ITR |
| $t_{truck}$ | transit time between ILN and CLN | hours |
| $t_{van}$ | transit time between CLN and CMFMB | hours |
| $t_{cargo}^{truck}$ | e-truck loading/unloading time | hours |
| $t_{cargo}^{van}$ | e-van loading/unloading time | hours |
| $t_{cargo}^{CLN}$ | cargo handling time in CLN | hours |
| $d_{truck}$ | distance between ILN and CLN | km |
| $d_{van}$ | distance between CLN and CMFMB | km |
| $v_{truck}$ | e-truck average speed in transit between ILN and CLN | km/h |
| $v_{van}$ | e-van average speed in transit between CLN and CMFMB | km/h |
| $NW$ | nighttime window for e-truck trunsfers | hours |
| $DW$ | daytime window for e-van trunsfers | hours |
| Dependent parameters | | |
| $D_{md}^{CLN}$ | demand for *d* day and *m* type of production material ordered by CLN | ITR |
| $D_{md}^{CMFMB}$ | demand for *d* day and *m* type of production material ordered by CMFMB | ITR |
| $D'^{CMFMB}_{md}$ | reduced demand for *d* day and *m* type of production material ordered by CMFMB | ITR |
| $D''^{CMFMB}_{md}$ | reduced demand for *d* day and m type of production material ordered by CMFMB and calculated in full ITR units | ITR |
| $e_d^{truck}$ | total surplus volume of production materials delivered by e-trucks before *d* day | ITR |
| $e_{md}^{truck}$ | surplus volume of m type of production material delivered by e-trucks before *d* day | ITR |
| $e_d^{van}$ | total surplus volume of production materials delivered by e-vans before *d* day | ITR |
| $e_{md}^{van}$ | surplus volume of m type of production material delivered by e-vans before *d* day | ITR |
| $M_{truck}$ | minimum number of e-trucks (transfer ILN–CLN) | e-trucks |
| $L_{truck}$ | number of e-truck roundtrips per night (transfer ILN–CLN) | round-trips |
| $M_{van}$ | minimal number of e-van (transfer CLN–CMFMB) | e-vans |
| $L_{van}$ | number of e-van roundtrips per day (transfer CLN–CMFMB) | round-trips |
| $N_d^{van}$ | number of e-van transfers from CLN to CMFMB on *d* day | transfers |
| $N_d^{truck}$ | number of e-truck transfers from ILN to CLN on *d* day | transfers |
| $S_{md}^{CMFMB}$ | supply of *m* type of production material based on order of CMFMB on *d* day | ITR |

**Table 1.** *Cont.*

| Index: | | Unit |
|---|---|---|
| $S_{md}^{CLN}$ | supply of *m* type of production material based on order of CLN on *d* day | ITR |
| $Q_{md}^{CLN}$ | overnight stock of production materials in CLN after *d* day | ITR |
| $Q_{d}^{CMFMB}$ | total overnight stock in CMFMB after *d* day | tonnes, ITR |
| $Q_{md}^{CMFMB}$ | overnight stock of *m* type of production material in CMFMB after *d* day | tonnes, ITR |
| $P_{d}^{CMFMB}$ | total demand for production material in non-unitized form ordered by CMFMB for d day | %, tonnes |
| $P_{md}^{CMFMB}$ | demand for d day and m type of production material in non-unitized form ordered by CMFMB | %, tonnes |
| $T_{lead}$ | supplier lead time | hours |
| $t_{storage}$ | cargo storage time in CLN | hours |

### 4.3. Assumptions

For the quantitative analyses, assumptions were made for the decision support model for LSCM in CMFMCs. The transport process should apply the principles of sustainability in practice, so that the transport has as little negative impact as possible on the environment and society. In practice, this means the maximum possible use of the loading capacity of vehicles, eliminating congestion, and minimizing harmful transport-born emissions. Hence, it was assumed that deliveries to the urban agglomeration area will be made by rail, using intermodal terminal located in the ILN. The CMFMC supply chain does not assume the use of classic intermodal transport, in which the same loading unit is transported door-to-door by rail and road. Intermodal transport units such as containers, swap bodies, and road trailers used for long-distance transport will be changed at the ILN for IRT units better suited for city logistics needs. Within the urban agglomeration area, the IRT units will be transferred by road transport, firstly to CLNs and finally to CMFMBs, using matched delivery trucks. Detailed assumptions for the CMFMC supply chain model include:

(1) All vehicles used are electrically powered and a sufficient number of charging points are located at the ILN and each CLN.
(2) Transit between the ILN and the CLN, i.e., the first leg of the CMFMC supply chain, is performed by e-trucks with a minimum capacity of 18 tonnes.
(3) E-truck use only two-line roads, i.e., the city ring road and the main entrance roads connecting the ring road with the CLNs located in different urban districts (Figure 4).
(4) Transit between the CLN and CMFMBs in one CMFMC, i.e., the second leg of the CMFMC supply chain, is performed by e-vans with a maximum capacity of 3.5 tonnes.
(5) E-vans use all roads, including local ones, within a given CMFMC area.
(6) Deliveries using e-trucks to each CLN are made at night once a day, which allows the creation of a convoy of vehicles in transit.
(7) Deliveries using e-vans take place during the working hours of CMFM companies and in consultation with them, i.e., in a flexible manner, but outside peak traffic hours.
(8) There are two types of ITR storage areas in each CLN, i.e., the first one for the needs of buffer ITR storage and facilitating day shipments to CMFMBs, and the second one for overnight storage of ITRs that are waiting for next-day transfer.
(9) In each CMFMB, there is a designated storage area for production materials delivered in ITRs, and this means that the ITRs are emptied in the CMFMBs and their capacity is used to transport finished products and production waste on the return transfer to the CLN.

(10) Regardless of the number of e-truck and e-van vehicles used to perform a specific cargo transfer, their capacity is always used in such a way that only one vehicle (the last one loaded in a given transfer) is allowed to be not fully loaded. It is assumed that this vehicle can be loaded from 50% to 100% of its capacity.
(11) Orders from CMFM enterprises for production materials are processed according to two rules: 'next-day delivery', i.e., orders are collected on a given day and delivered the next day, and 'never less than ordered', i.e., the volume of transported materials can be increased due to the best use of the vehicle's cargo capacity. Hence, each daily delivery to the CLN is the result of summing up orders submitted by individual CMFMBs when planning the next production day, considering corrections resulting from the overnight stock in the CLN and the need to use e-truck capacity. Similarly, each daily delivery to the CMFMB corresponds to its previously ordered demand, which should consider the overnight stock in CMFM and the need to use e-van capacity.
(12) CMFMB specialization is based on the technological processes used. The floor-by-floor placement of the same type of technological equipment, considering the balance of production capacities and existing transport, energy, and utility limitations, makes it possible to reduce the range of materials supplied, and loading–unloading and sorting operations in the ILN and CLNs [7,56]. Therefore, deliveries to each CMFMB comprise up to several dozen types of materials commonly used in production.
(13) The demand for production materials ordered by CMFM companies is highly variable because it is related to the volume of next-day planned production and to the JIT ordering regime.
(14) The finite production capacity of CMFMBs in each CMFMC is the same.

## 5. Results

### *5.1. A Decision Support Model of Lean Supply Chain Management for CMFM Clusters*

The mathematical model presented is a classic deterministic model built using MATLAB programming (version R2024a) and the numeric computing platform. Its advantage is that the model is easy to expand with new calculation modules and is compatible with other modeling and simulation platforms and environments. It is based on the input data, e.g., demand for production material and level of utilization of vehicles. The output data (e.g., overnight stock of production materials, number of road transfers) are calculated using mathematical formulas. The proposed model gives a well-determined solution, taking into account all of the adopted assumptions and following steps.

The task is to determine the number of transported ITR units between ILN–CLN–CMFMB in such a way as to fill the vehicles for the assumed coefficient $C^{van}$ and $C^{truck}$. The total CMFMB demand on $d$ day is given by formula:

$$P_d^{CMFMB} = \sum_{m \in \{A,B,C,\ldots\}} P_{md}^{CMFMB} \tag{1}$$

The $P_d^{CMFMB}$ demand for each production material is converted into ITR units using $SF_m$ stowage factor of $m$ type of production material loaded in ITR.

$$D_{md}^{CMFMB} = P_{md}^{CMFMB} \cdot SF_m. \tag{2}$$

The current CMFMB order of $m$ type of production material for $d$ day is given by the formula:

$$D'^{CMFMB}_{md} = \begin{cases} 0 & if\ D_{md}^{CMFMB} < \mathrm{Q}_{\mathrm{m(d-1)}}^{\mathrm{CMFMB}}\ \ or\ \ D_{md}^{CMFMB} = 0, \\ D_{md}^{CMFMB} - \mathrm{Q}_{\mathrm{m(d-1)}}^{\mathrm{CMFMB}} & if\ D_{md}^{CMFMB} \geq \mathrm{Q}_{\mathrm{m(d-1)}}^{\mathrm{CMFMB}} \end{cases} \tag{3}$$

It was assumed that full ITR units would be transported. The number $D'^{CMFMB}_{md}$ should be rounded using the formula:

$$D''^{CMFMB}_{md} = \left\lceil D'^{CMFMB}_{md} \right\rceil \tag{4}$$

The number of e-vans needed on $d$ day for transportation between the CLN and CMFMB is expressed by the formula:

$$N^{van}_{d} = \left\lceil \frac{\sum_{m \in \{A,B,C,\ldots\}} D''^{CMFMB}_{md}}{R^{van}} \right\rceil \tag{5}$$

If the number of ITRs in the current order is insufficient, i.e., the last e-van is filled below the assumed level of utilization $C^{van}$, then surplus ITR units are loaded. The number of additional ITR units is expressed as follows:

$$e^{van}_{d} = N^{van}_{d} \cdot R^{van} - \sum_{m \in \{A,B,C\ldots\}} D''^{CMFMB}_{md} \tag{6}$$

and

$$e^{van}_{d} = \sum_{m \in \{A,B,C,\ldots\}} e^{van}_{md} \tag{7}$$

As a result, the demand ordered by the CMFMB is expressed as follows:

$$S^{CMFMB}_{md} = D''^{CMFMB}_{md} + \mathrm{e}^{van}_{md} \tag{8}$$

All CMFMBs in the CMFMC are supplied by one CLN. For model simplicity, all CMFMBs on a given day generate the same amount of demand for particular materials. Hence, the total demand generated by the CMFMC, i.e., the order submitted by the CLN, depends only on $n$ number of CMFMBs in the cluster. The demand ordered by the CLN is expressed as follows:

$$D^{CLN}_{md} = n \cdot S^{CMFMB}_{md} \tag{9}$$

Similar to CMFMB orders, the current CLN order of $m$ type of production material for $d$ day is given by the formula:

$$D'^{CLN}_{md} = \begin{cases} 0 & if\ D^{CLN}_{md} < Q^{CLN}_{m(d-1)}\ or\ D^{CLN}_{md} = 0, \\ D^{CLN}_{md} - Q^{CLN}_{md} & if\ D^{CLN}_{md} \geq D^{CLN}_{m(d-1)} \end{cases} \tag{10}$$

The number of e-trucks needed on $d$ day for transportation between ILN and CLN is expressed by the formula:

$$\left\lceil N^{truck}_{d} = \frac{\sum_{m \in \{A,B,C,\ldots\}} D'^{CLN}_{md}}{R^{truck}} \right\rceil \tag{11}$$

If the number of ITRs in the current order is insufficient, i.e., the last e-truck is filled below the assumed level of utilization $C^{truck}$, then surplus ITR units are loaded. The number of additional ITR parcels is expressed as follows:

$$e^{truck}_{d} = N^{truck}_{d} \cdot R^{truck} - \sum_{m \in \{A,B,C,\ldots\}} D'^{CLN}_{md} \tag{12}$$

and

$$e^{truck}_{d} = \sum_{m \in \{A,B,C,\ldots\}} e^{truck}_{md} \tag{13}$$

As a result, the demand reported by the CLN is expressed as follows:

$$S_{md}^{CLN} = D'^{CLN}_{md} + e_{md}^{truck} \tag{14}$$

E-truck deliveries between the ILN and CLN are performed at night. As the transport time window is limited, it is necessary to estimate the minimum number of e-trucks needed. The number of e-trucks is given by the formula:

$$\left\lceil M_{truck} = \frac{\max_{d}\left\{N_d^{truck}\right\}}{L_{truck}} \right\rceil \tag{15}$$

Similarly, regarding e-van day transit during the day, the number of e-vans is given by the formula:

$$\left\lceil M_{van} = \frac{\max_{d}\left\{N_d^{van}\right\}}{L_{van}} \right\rceil \tag{16}$$

where $L_{truck}$ is the number of e-truck roundtrips per night and $L_{van}$ is the number of e-van roundtrips per day, excluding morning and evening rush hours. They are determined on the basis of the time needed for transport in two legs of the CMFMC supply chain.

$$L_{truck} = \left\lfloor \frac{NW}{2 \cdot t_{truck}} \right\rfloor \tag{17}$$

$$L_{van} = \left\lfloor \frac{DW}{2 \cdot \ t_{van}} \right\rfloor \tag{18}$$

where:

$$t_{truck} = \frac{d_{truck}}{v_{truck}} + 2 \cdot \mathrm{t}_{\mathrm{cargo}}^{\mathrm{truck}} \tag{19}$$

$$t_{van} = \frac{d_{van}}{v_{van}} + 2 \cdot \mathrm{t}_{\mathrm{cargo}}^{\mathrm{van}} \tag{20}$$

Distances $d_{truck}$, $d_{van}$ and speeds $V_{truck}$, $V_{van}$ are known.

Having the transfer time and loading/unloading time in two sections of the supply chain $\left(t_{truck}\ ,\ \ t_{van},\ t_{cargo}^{truck}, t_{cargo}^{van}\right)$ and cargo handling time in CLN $\mathrm{t}_{\mathrm{cargo}}^{CLN}$, you can calculate the supplier lead time as follows:

$$T_{lead} = t_{truck} + t_{van} + 2 \cdot t_{cargo}^{truck} + 2 \cdot t_{cargo}^{van} + t_{cargo}^{CLN} + t_{storage} \tag{21}$$

The verification and validation of the proposed decision support model for LSCM in CMFMCs performed based on the case study analysis using MATLAB are presented in the next part.

### 5.2. A Case Study

#### 5.2.1. Model Inputs

The CMFMC supply chain model was verified using appropriately selected test data. The test data describe a typical CMFM manufacturing system and its associated supply chain, consistent with the spatial relationships shown in Figures 1 and 4. The input data were determined using the expert method and refer to standard values of urban transport system parameters found in European cities that have a high potential for implementing the CMFMC system i.e., Berlin, Amsterdam, Lodz, etc. The test data for the CMFMC supply chain model shown include:

(1) The analysis period is 1 year, i.e., 365 daily orders placed by CMFMBs.
(2) The maximum cargo capacity of vehicles used in urban road transport are:
e-van—6 ITR
e-truck—24 ITR
(3) The minimum level of cargo capacity utilization of e-vans and e-trucks may be 50%, 67%, 83%, or 100%, defining the analysis variants (Table 2).
(4) The demand ordered by CMFMBs relates to three types of production materials, i.e., A, B, or C, constituting cargo transported in ITRs. Additionally, only one production material can be transported in one ITR unit. The stowage factor of an ITR unit for specific materials is:
$SF_A$—0.5 t/ITR
$SF_B$—0.4 t/ITR
$SF_C$—0.2 t/ITR
(5) The number of CMFMBs supplied by one CLN within the area of one CMFMC is $n$ = 2, $n$ = 4, $n$ = 6, or $n$ = 8, defining the analysis variants.
(6) Demand ordered by each CMFM building is generated randomly for each day and each production material, and its maximum value for one material is 3 tons/day, i.e., the daily demand may be 0% to 100% of the maximum value.
(7) Parameters that determine supplier lead time:
$d_{truck}$ = 30 km, $d_{van}$ = 5 km
$v_{truck}$ = 40 km/h, $v_{van}$ = 20 km/h
$t^{CLN}_{cargo}$ = 0.20 h
$t^{truck}_{cargo}$ = 0.20 h, $t^{van}_{cargo}$ = 0.15 h
$t_{storage}$ = 0.00 h ÷ 11:00 h
$DW$ = 8.00 h (from 10:00 to 15:00 and from 19:00 to 22:00)
$DW$ = 8.00 h (from 22:00 to 06:00)
$L_{truck}$ = 3 roundtrips, $L_{van}$ = 6 roundtrips

**Table 2.** Demand for production material ordered by one CMFMB.

| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | ... | 365 |
|---|---|---|---|---|---|---|---|---|---|
| $P_{Ad}$ [%] | 67% | 30% | 66% | 33% | 77% | 66% | 61% | ... | 57% |
| $P_{Bd}$ [%] | 74% | 53% | 95% | 18% | 50% | 85% | 92% | ... | 39% |
| $P_{Cd}$ [%] | 90% | 24% | 28% | 45% | 42% | 52% | 8% | ... | 99% |
| $P_{Ad}$ [t] | 2.00 | 0.89 | 1.98 | 1.00 | 2.32 | 1.99 | 1.83 | ... | 1.71 |
| $P_{Bd}$ [t] | 2.22 | 1.59 | 2.85 | 0.53 | 1.51 | 2.54 | 2.77 | ... | 1.17 |
| $P_{Cd}$ [t] | 2.71 | 0.73 | 0.83 | 1.35 | 1.27 | 1.57 | 0.25 | ... | 2.97 |
| $D_{Ad}$ [ITR] | 4.00 | 1.78 | 3.96 | 2.00 | 4.64 | 3.98 | 3.66 | ... | 3.48 |
| $D_{Bd}$ [ITR] | 5.55 | 3.98 | 7.13 | 1.33 | 3.78 | 6.35 | 6.93 | ... | 1.73 |
| $D_{Cd}$ [ITR] | 13.55 | 3.65 | 4.15 | 6.75 | 6.35 | 7.85 | 1.25 | ... | 0.30 |

### 5.2.2. Model Outputs

The logic of the quantitative analysis using the CMFMC supply chain model is presented in the tables below. Table 3 shows the calculations regarding e-van transit between the CLN and CMFMBs and overnight stock in CMFM buildings for the assumed level of e-van capacity utilization $C^{van}$ = 83%. In the first step, the daily demand for each production material ordered by one CMFMB ($D_{md}$) is reduced by the surplus volumes of production materials $e^{van}_{md}$ that were delivered in previous days. These surplus materials result from the 'never less than ordered' principle of the CMFMC supply chain and are directly related to the assumed level of e-van capacity utilization. The value of reduced demand $D'^{CMFMB}_{md}$ is then converted into full ITR units $D''^{CMFMB}_{md}$ and into the respective number of e-van transfers $N^{truck}$. As a result, each day, a precisely calculated volume of each production material is delivered by e-vans $S_{md}^{CMFMB}$, which generates a variable level of overnight stock in each of the supplied CMFMBs $Q_{md}$. The overnight stock at CMFMBs is measured in tons because ITR units are unloaded on site to be used afterward for transport finished products and production waste on the return transfer to the CLN.

**Table 3.** Demand for of e-van transit and overnight stock in CMFM buildings ($C^{van}$ = 83%).

| **Day** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **...** | **365** |
|---|---|---|---|---|---|---|---|---|---|
| $D'^{CMFMB}_{Ad}$ [ITR] | 4.00 | 1.78 | 2.74 | 0.74 | 2.38 | 3.36 | 1.02 | ... | 2.64 |
| $D'^{CMFMB}_{Bd}$ [ITR] | 5.55 | 3.53 | 6.65 | 0.00 | 2.78 | 6.13 | 5.05 | ... | 2.48 |
| $D'^{CMFMB}_{Cd}$ [ITR] | 13.55 | 3.20 | 3.35 | 5.10 | 4.45 | 7.30 | 0.00 | ... | 13.90 |
| $D''^{CMFMB}_{Ad}$ [ITR] | 4 | 2 | 3 | 1 | 3 | 4 | 2 | ... | 3 |
| $D''^{CMFMB}_{Bd}$ [ITR] | 6 | 4 | 7 | 0 | 3 | 7 | 6 | ... | 3 |
| $D''^{CMFMB}_{Cd}$ [ITR] | 14 | 4 | 4 | 6 | 5 | 8 | 0 | ... | 14 |
| $\sum_{m\in\{A,B,C\}} D''^{CMFMB}_{md}$ [ITR] | 24 | 11 | 17 | 11 | 11 | 23 | 11 | ... | 23 |
| $N^{van}$[e-van] | 4 | 2 | 3 | 2 | 2 | 4 | 2 | | 4 |
| $e^{van}_{A}$ [ITR] | 0 | 1 | 1 | 2 | 0 | 2 | 1 | ... | 1 |
| $e^{van}_{B}$ [ITR] | 0 | 0 | 1 | 1 | 0 | 1 | 1 | ... | 1 |
| $e^{van}_{C}$ [ITR] | 0 | 0 | 1 | 1 | 0 | 1 | 1 | ... | 1 |
| $S^{CMFMB}_{Ad}$ [ITR] | 4 | 3 | 4 | 3 | 3 | 6 | 3 | | 4 |
| $S^{CMFMB}_{Bd}$ [ITR] | 6 | 4 | 8 | 1 | 3 | 8 | 7 | | 4 |
| $S^{CMFMB}_{Cd}$ [ITR] | 14 | 4 | 5 | 7 | 5 | 9 | 1 | | 15 |
| $Q_{Ad}$ [ITR] | 0.00 | 1.22 | 1.26 | 2.26 | 0.62 | 2.64 | 1.98 | | 1.36 |
| $Q_{Bd}$ [ITR] | 0.45 | 0.48 | 1.35 | 1.00 | 0.23 | 1.88 | 1.95 | | 1.53 |
| $Q_{Cd}$ [ITR] | 0.45 | 0.80 | 1.65 | 1.90 | 0.55 | 1.70 | 1.00 | | 1.10 |
| $Q_{Ad}$ $[t]$ | 0.00 | 0.61 | 0.63 | 1.13 | 0.31 | 1.32 | 0.99 | | 0.68 |
| $Q_{Bd}$ $[t]$ | 0.18 | 0.19 | 0.54 | 0.40 | 0.09 | 0.75 | 0.78 | | 0.61 |
| $Q_{Cd}$ $[t]$ | 0.09 | 0.16 | 0.33 | 0.38 | 0.11 | 0.34 | 0.20 | | 0.22 |

Table 4 presents the second-step calculations regarding e-truck transit between the ILN and CLN and overnight stock in the CLN for the assumed number of CMFM buildings in the CMFMC and for the assumed level of e-truck capacity utilization $C^{truck}$ = 83%. The difference between the calculations presented in Table 3 compared to the previous ones presented in Table 3 results from the summation of demand generated by the CMFMBs and the use of bigger capacity e-trucks. At the first leg of the CMFMC supply chain, i.e., the ILN–CLN stage of the supply chain, ITR units are used without their unloading, including the overnight storage period in the CLN.

Finally, supplier lead time is calculated for any ITR transported from the ILN to CMFMBs, as follows:

$$T_{lead} = \frac{d_{truck}}{v_{truck}} + \frac{d_{van}}{v_{van}} + 2 \cdot t^{truck}_{cargo} + 2 \cdot t^{van}_{cargo} + t^{CLN}_{cargo} + t_{storage} = \frac{30}{40} + \frac{5}{20} + 0.40 + 0.30 + 0.20 + t_{storage} = 1.90\ \text{h} + t_{storage}$$

**Table 4.** Demand for of e-truck transit and overnight stock in the CLN ($n = 6, C^{truck}$ = 83%).

| **Day** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | ... | **365** |
|---|---|---|---|---|---|---|---|---|---|
| $D_{Ad}^{CLN}$ [ITR] | 24 | 18 | 24 | 18 | 18 | 36 | 18 | ... | 24 |
| $D_{Bd}^{CLN}$ [ITR] | 36 | 24 | 48 | 6 | 18 | 48 | 42 | ... | 24 |
| $D_{Cd}^{CLN}$ [ITR] | 84 | 24 | 30 | 42 | 30 | 54 | 6 | ... | 90 |
| $D_{Ad}^{CLN} + D_{Bd}^{CLN} + D_{Cd}^{CLN}$ [ITR] | 144 | 66 | 102 | 66 | 66 | 138 | 66 | ... | 138 |
| $N_d^{truck}$ [e-truck] | 6 | 3 | 5 | 3 | 2 | 6 | 3 | ... | 6 |
| $e_{\mathrm{Ad}}^{truck}$ [ITR] | 0 | 1 | 6 | 6 | 0 | 1 | 2 | ... | 1 |
| $e_{\mathrm{Bd}}^{truck}$ [ITR] | 0 | 1 | 5 | 6 | 0 | 1 | 1 | ... | 1 |
| $e_{\mathrm{Cd}}^{truck}$ [ITR] | 0 | 0 | 5 | 6 | 0 | 0 | 1 | ... | 0 |
| $S_{Ad}^{CLN}$ [ITR] | 24 | 19 | 29 | 18 | 12 | 37 | 19 | ... | 25 |
| $S_{Bd}^{CLN}$ [ITR] | 36 | 25 | 52 | 7 | 12 | 49 | 42 | ... | 25 |
| $S_{Cd}^{CLN}$ [ITR] | 84 | 24 | 35 | 43 | 24 | 54 | 7 | ... | 90 |
| $Q_{\mathrm{Ad}}^{\mathrm{CLN}}$ [ITR] | 0 | 1 | 6 | 6 | 0 | 1 | 2 | ... | 1 |
| $Q_{\mathrm{Bd}}^{\mathrm{CLN}}$ [ITR] | 0 | 1 | 5 | 6 | 0 | 1 | 1 | ... | 1 |
| $Q_{\mathrm{Cd}}^{\mathrm{CLN}}$ [ITR] | 0 | 0 | 5 | 6 | 0 | 0 | 1 | ... | 0 |

#### 5.2.3. Verification and Validation of the Proposed Decision Support Model

The verification of the proposed decision support model for LSCM in CMFMCs is implemented using MATLAB based on a case study analysis.

The obtained results of the conducted quantitative analysis using the CMFMC supply chain model allowed the following conclusions to be drawn (Tables 5 and 6):

(1) Increasing the number of CMFMBs in the cluster increases the number of e-truck transfers to the CLN, i.e., 4 times more CMFMBs (from n = 2 to n = 8) generates from 3.39 to 3.99 times more e-truck transfers, depending on the variant of cargo capacity utilization (Figure 5).

(2) Increasing the number of CMFMBs in the cluster gives the benefit of reducing the transport performance per one ITR delivered, i.e., 4 times more CMFMBs (from n = 2 to n = 8) generates a decrease in e-truck transport performance of up to 15%, depending on the variant of cargo capacity utilization.

(3) Increasing the number of CMFMBs in the cluster does not result in an increase in the average and maximum volume of ITRs that are stored overnight in the CLN.

(4) The average and maximum volume of ITRs that are stored overnight in the CLN is strongly dependent on the e-truck cargo capacity utilization variant, i.e., the lower the level of e-truck cargo capacity utilization, the lower the demand for storage area in the CLN. Reducing the level of e-truck capacity utilization by 50% (from 100% to 50%) generates a lower maximum demand for storage area in the CLN of up to 64% and a lower average demand for storage area in the CLN of up to 91% (Figure 6).

(5) The average and maximum volume of ITRs that are stored overnight in one CMFMB is strongly dependent on the e-van cargo capacity utilization variant, i.e., the lower the level of e-van cargo capacity utilization, the lower the demand for storage area in CMFMC buildings. Reducing the level of e-van capacity utilization by 50% (from 100% to 50%) generates a lower maximum demand for storage area in the CMFMBs of up to 60% and a lower average demand for storage area in the CMFMBs of up to 79%.

(6) The choice of the variant of e-truck cargo capacity utilization is to a small extent related to the increase in the number of e-truck transfers. Reducing the level of e-truck capacity utilization by 50% (from 100% to 50%) generates an increase in the number of e-truck transfers from 6% to 24%, depending on the number of CMFMBs in the cluster.

(7) The choice of the variant of e-van cargo capacity utilization is to a very small extent related to the increase in the number of e-van transfers. Reducing the level of e-van capacity utilization by 50% (from 100% to 50%) generates an increase in the number of e-van transfers of up to 11%.

(8) The delivery time of production materials to CMFMBs is 1.20 h. This supplier lead time is only achievable when the cargo transported in the ITR is directly transferred from the e-truck to the e-van without the need for storage in the CLN. This scenario occurs very rarely in practice. The buffer storage time depends on the time difference between the times of e-truck arrival at the CLN and e-van departure from the CLN, which may range from 0.00 h up to 11:00 h.

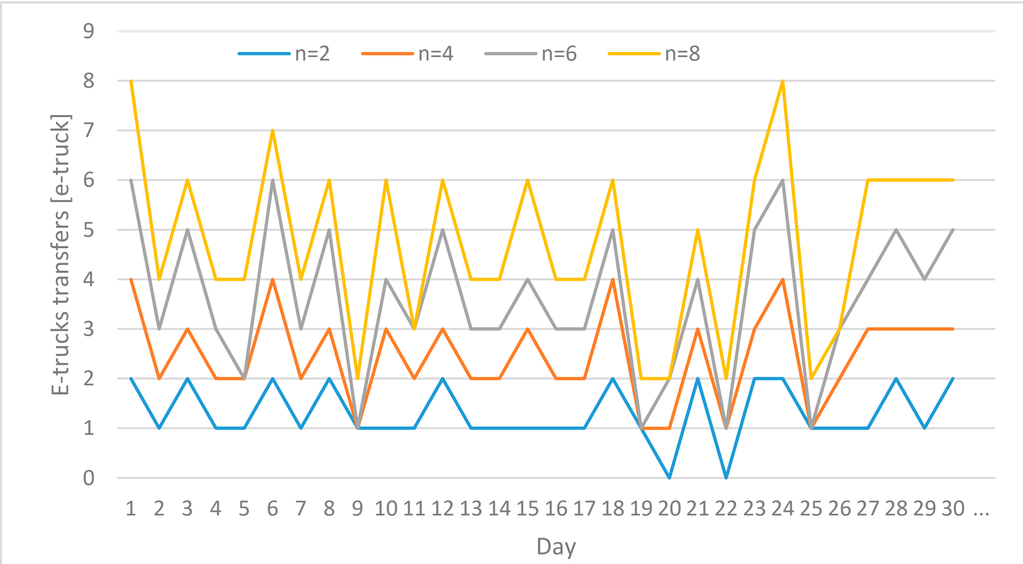



**Figure 5.** Number of e-truck transfers to the CLN in relation to the number of CMFMBs in the cluster.

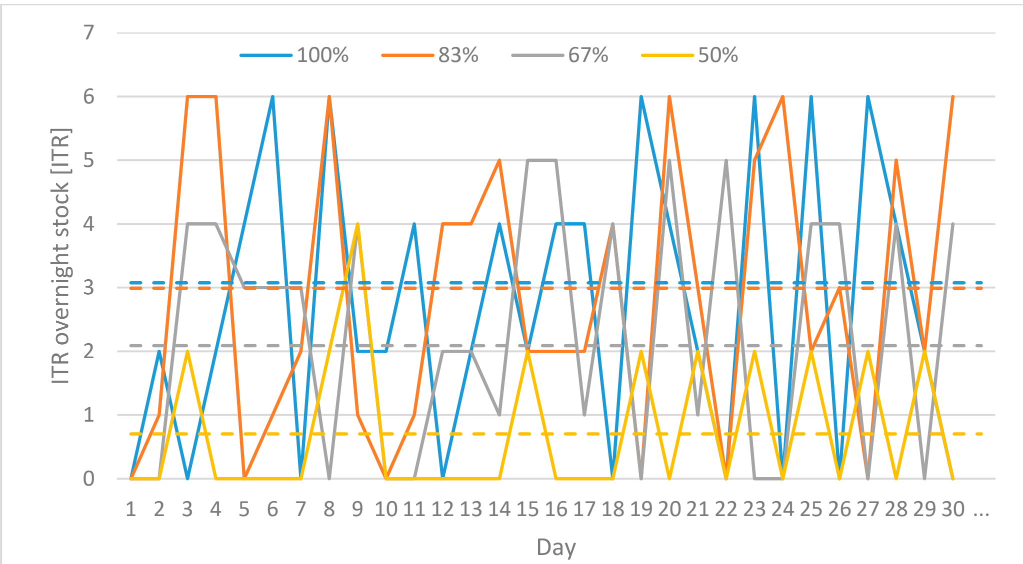



**Figure 6.** The volume of ITRs that are stored overnight in the CLN in relation to the e-truck cargo capacity utilization variant—daily and 365-day average data.

**Table 5.** Matrix of model outputs related e-van transit and overnight stock in CMFMBs.

| $C^{van}$ | **100%** | **83%** | **67%** | **50%** |
|---|---|---|---|---|
| avg. $Q^{CMFMB}$ | 2.52 | 1.77 | 0.95 | 0.53 |
| max. $Q^{CMFMB}$ | 5.00 | 4.00 | 3.00 | 2.00 |
| avg. $N^{van}$ | 2.49 | 2.60 | 2.70 | 2.77 |
| max. $N^{van}$ | 5 | 5 | 5 | 5 |
| $M_{van}$ | 1 | 1 | 1 | 1 |

**Table 6.** Matrix of model outputs related e-truck transit and overnight stock in the CLN.

| | $C^{truck}$ | **Number of CMFMBs** | | | |
|---|---|---|---|---|---|
| | | **n = 2** | **n = 4** | **n = 6** | **n = 8** |
| avg. $Q^{CLN}$ | 100% | 10.88 | 10.75 | 9.11 | 8.17 |
| max. $Q^{CLN}$ | 100% | 23.00 | 23.00 | 22.00 | 21.00 |
| avg. $N^{truck}$ | 100% | 1.24 | 2.47 | 3.70 | 4.93 |
| max. $N^{truck}$ | 100% | 3 | 5 | 7 | 10 |
| avg. $Q^{CLN}$ | 83% | 7.45 | 1.88 | 8.15 | 7.24 |
| max. $Q^{CLN}$ | 83% | 19.00 | 16.00 | 19.00 | 18.00 |
| avg. $N^{truck}$ | 83% | 1.38 | 2.61 | 3.85 | 5.07 |
| max. $N^{truck}$ | 83% | 3 | 5 | 8 | 10 |
| $M_{truck}$ | 83% | 1 | 2 | 3 | 4 |
| avg. $Q^{CLN}$ | 76% | 5.02 | 0.08 | 5.59 | 0.77 |
| max. $Q^{CLN}$ | 76% | 16.00 | 13.00 | 16.00 | 8.00 |
| avg. $N^{truck}$ | 76% | 1.47 | 2.61 | 3.95 | 5.21 |
| max. $N^{truck}$ | 76% | 3 | 5 | 8 | 10 |
| $M_{truck}$ | 76% | 1 | 2 | 3 | 4 |
| avg. $Q^{CLN}$ | 50% | 1.37 | 0.02 | 2.04 | 0.01 |
| max. $Q^{CLN}$ | 50% | 10.00 | 8.00 | 10.00 | 4.00 |
| avg. $N^{truck}$ | 50% | 1.54 | 2.61 | 4.04 | 5.21 |
| max. $N^{truck}$ | 50% | 3 | 5 | 8 | 10 |
| $M_{truck}$ | 50% | 1 | 2 | 3 | 4 |

The obtained results of the case study showed the possibility of using the proposed decision support model for LSCM in CMFMCs [49].

## 6. Discussion

Some managerial and practical implications of the presented decision support model for LSCM in CMFMCs on material flows, value streams, and decision making in real time using I4.0 technologies are as follows [17,42,61,62]:

- The presented decision support model could help stakeholders of CMFMCs (consumers, suppliers, and service providers) to optimize the economic, environmental, and social performance of operations in supply chains [63]. The model allows for the detection of irregularities and bottlenecks in the CMFMC supply chain and, more importantly, it is an effective tool for supporting the improvement of the efficiency of the analyzed processes [64–66]. For example, the model directly allows for the optimization of storage space in the CLN, determining the appropriate number of e-vans and e-trucks to carry out transfer operations and selecting the best option for the capacity utilization level of these vehicles.

- The continuous LSCM process is implemented using the platform of service supply chain (PSSC), which uses I4.0 technologies and enables interaction between all stakeholders of the CMFMCs in order to improve the efficiency of real-time value co-creation and dynamic configuration of logistics operations [7,67].
- A necessary condition for obtaining the necessary data that constitute the model inputs is the use of modern information, communication, and telematics technologies that constitute the foundation of I4.0 technologies. The number of available technical and organizational solutions within I4.0 technologies that can be used in the CMFMC supply chain is numerous. It is rational to implement systems that are already known on a global scale and proven in agglomeration logistics and at the same time have great development potential.
- Key technologies that should support LSCM in CMFMCs include: IoT used in cargo handling areas (ILN, CLN), means of transport (e-vans, e-trucks), and IRTs; GPS system and video cameras for real-time monitoring of all areas requiring security; and database and blockchain systems for collecting and processing data while maintaining maximum security of operations throughout the supply chain [68–70].
- An extremely important aspect of the reliability of the examined supply chain is the arrangement of the e-truck and e-van charging process so that it does not interfere with the implementation of timely transfers. Full charging can be carried out during the night (for e-vans) or during the day (for e-trucks) and quick recharging during loading/unloading operations.
- This decision support model is to be tested and piloted in a large city, i.e., Berlin, Amsterdam, Lodz, etc. Lessons learned through using the proposed decision support system could present some tangible opportunities for improving and developing the model.

Thus, the conducted research outputs have relevant managerial and practical implications. The model turned out to be an effective decision support tool in the process of management of CMFMC supply chains. Especially, it facilitates the LSCM implementation process to achieve the expected results. It enables value stream mapping (VSM) and managing logistics processes and inventories in deliveries from ILNs to CMFMBs. Despite many simplifications and limitations, the presented model allows managers to learn about the key parameters of the logistics process and the relationships between them. Moreover, it allows managers to answer key questions regarding the economic, technical, and environmental effectiveness of these processes.

Based on the calculations performed using the representative test data, the previously asked research questions can be answered as follows.

(1) Ad RQ1. There is a clear proportional dependency between the number of CMFMBs supplied by the CLN and the number of e-trucks needed, as well as the number of transfers at the first leg of the CMFMC supply chain, i.e., ILN–CLN. There is no such dependence in relation to the second transport leg of the CMFMC supply chain, i.e., CLN–CMFMB in the cluster area. This is because in the adopted model, e-van deliveries to individual CMFM buildings are independent of each other. Importantly, there is an effect of scale in relation to the transport performance per one ITR delivered, which translates into a reduction in the unit cost of delivery calculated per 1 ITR.

(2) Ad RQ2. There is no dependency between the number of CMFMBs and the demand for cargo storage service in the CLN that supplies these buildings. This is a non-obvious observation and allows us to define guidelines for transport infrastructure designers and logistics operators. The presented analyses show that appropriate management in the 'next-day delivery' regime of input and output cargo traffic in the CLN is the key to minimizing storage services and having adequate storage areas for overnight storage.

(3) Ad RQ3. The level of utilization of vehicle loading capacity at the two inter-city transport legs, i.e., ILN–CLN and CLN–CMFMB, is strongly dependent on the volume of production materials that are stored overnight. In the adopted delivery model, the appropriate selection of vehicles and their loading variant allows for minimizing storage needs.
(4) Ad RQ4. The supplier lead time calculated for any ITR transported from the ILN to the CMFMB, i.e., both transport legs of the CMFMC supply chain, depends primarily on the storage time in the CLN. This time may range from zero to several hours, depending on the time difference between the e-truck's arrival at the CLN and the e-van's further journey to the CMFMB. An obvious factor that determines the supplier lead time is the average speed of vehicles in the agglomeration area as well as the time needed for cargo loading and handling operations.

## 7. Conclusions

In large cities, CMFMCs face growing challenges in implementing LSCM due to the intensity of urban traffic and uncertainty of supply. Therefore, decision support systems for LSCM can help service providers of CMFMCs to plan lean supply chains that aim to eliminate all types of waste, reduce the use of natural and energy resources, and continuously improve processes related to logistics activities [44,51]. This study analyzed the LSCM possibilities within CMFMCs as an integrated application of LM approaches and I4.0 technologies to manage the customer-centric value stream. The result of this analysis is the development of the decision support model for LSCM in CMFMCs, which justifies the minimization of the number of road transport transfers within the urban area and the amount of stock that is stored in CMFMBs and CLNs, and also adjusting supplier lead time for the cluster's finite production capacity conditions [12,55]. Moreover, the model provides an answer to the question of how the number of CMFMBs and their location in the agglomeration area will affect vehicle transport in the agglomeration area. Generally speaking, this decision support model could help CMFMC stakeholders to support sustainability in their supply chains. Decision makers could more easily achieve a balance between economic performance and environmental and social issues.

The limitations of the proposed decision support model for LSCM in CMFMCs are certainly related to the assumptions made in Section 4. The assumptions adopted were universal in nature so as to reflect the technical and organizational conditions of CMFMC supply chains in as many large cities as possible. Due to this, specific technological and system solutions that are implemented in a small number of agglomeration areas and have great development potential were not considered. These include urban rail, water, cable, or underground transport systems. These are also future technologies, such as autonomous vehicles, cargo drones, platooning of e-trucks, etc. A very important managerial limitation of the proposed model is the lack of opportunity to improve closed-loop supply chains. However, as the case study showed, these assumptions do not reduce the value of the proposed model.

The subsequent research will be related to the development of an integrated decision support model for LSCM in CMFMCs within the concept of the circular economy [71,72]. Further research on the model will consider return loads from CMFMBs, i.e., products and waste. The authors' intention is to optimize ITR loading through loading different types of production materials in one ITR. There is a plan to include transportation and storage costs as well as traffic disturbances in supply chains, e.g., congestion. Therefore, an extension of the model is planned. In future work, MCDA methods, multi-objective linear programming, and probability modules will be employed. The authors' ambition is to complete the research by creating a road map for implementing the CMFMC system in specific locations in Europe, i.e., in large agglomerations with extensive industrial areas similar to Berlin, Amsterdam, or Lodz.

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## Abbreviations

| | |
|---|---|
| CLC | city logistics center |
| CLN | city logistics node |
| CMFM | city multifloor manufacturing |
| CMFMB | city multifloor manufacturing building |
| CMFMC | city multifloor manufacturing cluster |
| GPS | global positioning system |
| HGV | heavy goods vehicles |
| ILN | intermodal logistics node |
| IoT | internet of things |
| IRT | intelligent reconfigurable trolley |
| ITP | idustrial and technology park |
| JIT | just-in-time |
| LM | lean manufacturing |
| LSCM | lean supply chain management |
| MFA | material flow analysis |
| PSSC | platform service supply chain |
| RFID | radio-frequency identification |
| SC | supply chain |
| SME | small and medium-sized enterprise |
| VSM | value stream mapping |

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