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# Smart Sustainable Production and Distribution Network Model for City Multi-Floor Manufacturing Clusters

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**Abstract:** This study focuses on management ways within a city multi-floor manufacturing cluster (MFMC). The application of MFMC in megapolises is closely related to the problem of urban spatial development and the problem of matching transport and logistics services. The operation of the MFMC depends on the efficiency of production and transport management considering technical, economic, end environmental factors. Therefore, conditions affecting decision-making in the field of production planning by MFMCs and accompanying transports within the agglomeration area with the use of the production-service platform were presented. Assumptions were created for the decision model, allowing for the selection of partners within the MFMC to execute the production order. A simplified decision model using the Hungarian algorithm was proposed, which was verified with the use of test data. The model is universal for material flow analysis and is an assessments basis for smart sustainable supply chain decision-making and planning. Despite the narrowing of the scope of the analysis and the simplifications applied, the presented model using the Hungarian algorithm demonstrated its potential to solve the problem of partner selection for the execution of the contract by MFMC.

**Keywords:** city multi-floor manufacturing; production and distribution processes planning; smart supply chain management; Hungarian algorithm; simplified decision model

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## 1. Introduction

City manufacturing of products and goods for the population has gone through many stages of development, from Handcraft Manufacturing [1] to Industry 4.0 (I4.0), within which paradigms such as Sustainable Development, Manufacturing Networks, Smart Manufacturing, Internet of Things, and Digital Twins have appeared [2–6]. A characteristic feature of city manufacturing is production and service enterprises operating in buildings that are located in the residential areas of megapolises [7]. Such a solution does not contradict the development of traditional industrial areas in agglomeration areas, i.e., production enterprises are located outside the residential area of the city in the industrial zones or industrial and technology parks (ITP) [7,8]. The purpose of city manufacturing is to meet the needs of the city's residents, as well as the needs of urban enterprises and technology development centers (further called advanced technology and education parks (ATEPs)), through the supply of goods and services in the framework of sustainable urban development [7,9].

The increase in cities' density and the intensity of urban traffic accelerates the development of solutions, such as city multi-floor manufacturing, especially in the vicinity of labor resources and customers [6,10,11]. Additionally, it is intensified by the following circumstances:

- high cost of urban plots and the rational use of land resources [12];
- limited capacities of transportation, environmental, and transport and logistics problems of the megapolis [3,12–15];
- sustainability of manufacturing and management in the framework of the I4.0 paradigm [5,6,16];
- development of small- and medium-sized businesses based on production–distribution networks organization [17–19];
- miniaturization of goods, the creation of innovative sustainable products for the city residents, and the efficient use of natural resources in the framework of circular economy [3,12,20];
- use of modular, lightweight technological equipment supplied in a disassembled state and assembled in production premises [21,22];
- change in quality of human resources [12,23].

A group of multi-floor manufacturing buildings located in the same residential area and a city logistics node (CLN) can be combined into a multi-floor manufacturing cluster (MFMC) [9,13]. The crucial support from municipalities are tax benefits and other incentives attracting small- and medium-sized enterprises (SMEs), and contributing to the sustainable development of the MFMCs in designated urban areas [3,24,25].

MFMC comprise production and service enterprises of various types of ownership, mainly SMEs, with different production orientations, with the presence of small-scale in-house equipment [19]. This feature of MFMC promotes business competition, allowing for creating collaborative and networked organizations [18] that can happen at some stages of development and can reach a level of a virtual manufacturing network based on Digital Twins models to fulfil customer orders [6,18].

The manufacturing network is one of the main forms of a production organization within the MFMC, and involves the creation of smart supply chain management (SCM) [18,26,27]. The specificity of internal and external processes of MFMC requires the use of appropriate management tools, i.e., models, methods, and software tools, which support operational planning and scheduling, monitoring production and logistics processes, as well as decision-making [6]. Therefore, this study proposes a model of MFMC production and distribution processes management that meets the needs of supply chains (SCs).

The study has the following structure. Section 2 presents the literature review of city manufacturing and their key elements. Section 3 presents materials and methods. Section 4 presents a model of MFMC production and distribution processes management in SC and a simulation case study. Section 5 discusses the research results, taking into account the limitations of the methodology used, and final conclusions are given in Section 6.

## 2. Literature Review

The literature review is structured to analyze literature in three research areas: city manufacturing and logistics, smart manufacturing and socio–cyber–physical manufacturing systems, and smart sustainable SCM for MFMC.

### 2.1. City Manufacturing and Logistics

Kühnle [28] defined the city manufacturing as a smart manufacturing system, which is located in an urban environment and is focused solely on supplying products to urban consumers. The sustainable development of megapolises contributed to the emergence of multi-floor manufacturing in residential areas, which led to the need to solve a number of problems associated with ensuring sustainable and green city manufacturing, technology and vehicles assessment, multi-floor layout design, selection of the technological equipment and vehicles (for example, pipe and freight elevators in buildings), and planning of production–distribution networks [22,29,30].

An important aspect of the sustainable development of city manufacturing is the formation of MFMCs with their own CLN, which are developed to solve city logistics problems by separating internal (within MFMC) and external material flows in conditions of intense urban traffic [9,13]. The input and output of material flows of cluster enterprises is carried out only through the CLN, where freights are temporarily stored and properly sorted. CLN also carries out warehouse activities within the MFMC [9]. Logistic problems within the MFMC are solved by harmonizing the production capacity with the throughput of the MFMC transport system, the main elements of which are freight elevators of the cluster's manufacturing buildings, internal and external vehicles, and intelligent reconfigurable trolleys (IRTs) [31]. CLN also serves for the selection of finished products and goods by customers, for example, by means of shops, pick-up points, and parcel lockers [9,32,33].

IRTs are designed for the transportation and temporary storage of solid, bulk, and liquid freights for both production needs and customers: materials, workpieces, components, semi-finished and finished products, repair and disposal of production equipment, and production waste [18,34,35]. IRTs can also be used as removable buffer drives in sections of automatic lines located on different floors of the MFMC building [36]. A special feature of IRTs is that they can be used both in the MFMC and outside it, including for container, multimodal, intermodal, and international transport, which significantly distinguishes them from automated guided vehicles (AGVs) or autonomous mobile robots (AMRs), intended only for use in the framework of the enterprises [7,37,38]. However, AGVs and AMRs interact with IRTs for the automation of loading/unloading operations [9,38]. IRTs also have a number of features that enable achieving the following goals [9,34,39]:

- to sow and secure various freights;
- to combine the group of IRTs to form a container city (CC) for transportation by vehicles;
- to use various means of transport;
- to monitor in real-time using a recording and transmitting devices for the implementation of the sustainable SCM concept.

The production logistics in the framework of the MFMC is aimed at minimizing traffic by increasing the use of the capacity of IRTs and vehicles. IRTs are loaded at production enterprises located on different floors of the MFMB and are transported to the buffer zone on the ground floor using freight elevators. Then, they are picked up in a CC for loading into the cargo vans and, after delivery to the CLN, the CCs are sorted again with the option of further transport outside the cluster area [9,40].

The future of city manufacturing and logistics in the digital age is linked to the development of smart manufacturing and to production–distribution networks [6,11,17,37].

### *2.2. Smart Manufacturing and Socio–Cyber–Physical Manufacturing Systems*

Smart manufacturing is a product of the Fourth Industrial Revolution, also known as Industry 4.0 [41], which is based on the wide use of advanced manufacturing solutions, additive manufacturing, information and communications technology, and cyber–physical systems [6,42–44]. National Institute of Standards and Technology [45] defined smart manufacturing as "fully-integrated and collaborative manufacturing systems that respond in real time to meet the changing demands and conditions in the factory, supply network, and customer needs". More recently, Ren et al. [46] defined smart manufacturing as "a new, networked and service-oriented manufacturing paradigm, which evolved from, but extends beyond, the traditional manufacturing and service modes, and integrates many advanced technologies such as IoT, industrial internet, cyber–physical systems, cloud computing, data mining, artificial intelligence, and big data analytics", which is in agreement with the two previous [4,41] and more recent definitions [6,42,47]. These technologies automatically collect and process data throughout a product's life cycle in order to adapt production and logistics processes to changing conditions due to emerging uncertainties in order to meet customer needs. It is obvious that smart manufacturing is relevant in today's competitive environment and the increasingly stringent and dynamic customer requirements that require efficient and flexible management of production and logistics processes [48].

Kusiak [4] presented the idea of smart manufacturing being based on six pillars:

- increase in the share of innovative technologies in production [6,10];
- innovative materials and technologies for their application [6];

- data, with the focus on "big data" [6,49];
- predictive design engineering with an assessment of production and transport technologies [22,31];
- sustainability of city manufacturing based on the triple bottom line (TBL) covering environmental, economic, and social aspects [3,50];
- resource sharing in a distributed manufacturing environment, and the creation of production–distribution networks [11,28,47].

Smart manufacturing systems are based on cyber–physical manufacturing systems (CPMS), which are the key enabling technologies used as augmented reality, Internet of Things (IoT), cloud computing, service-oriented computing, big data, and cyber security [42,47,51]. Monostori at al. [52] defined CPMSs as "systems of systems of autonomous and cooperative elements connecting with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks, enhancing decision-making processes in real-time, response to unforeseen conditions and evolution along time".

The advancement of CPMS does not reduce the human role in the management of smart manufacturing systems under uncertainty, but it helps experts and managers make faster and more informed decisions based on reliable information and assessments of intelligent expert systems, which contributes to a better interaction between humans and machines, as well as between manufacturers, suppliers, and customers. The complexity of interrelated production problems, emerging uncertainties in SCs, and the need for prompt and balanced decision-making require the human involvement in the CPMS. Thus, the integration of social aspects and CPMSs is the basis for the development of socio–cyber–physical manufacturing systems, which should consider the human factor in the smart SCM within the production–distribution network [6]. The role and importance of the socio–cyber–physical manufacturing systems increases significantly in the context of smart and distributed manufacturing, when there is a need to manage SCs within production–distribution networks under uncertainty for both the production capabilities of virtual enterprises and the SCs in real time [6,52,53]. Thus, smart manufacturing and socio–cyber–physical systems are the most efficient production–distribution networks systems in the framework of MFMC.

In the framework of the smart manufacturing paradigm, a service-oriented networked product development model is realized, based on cloud-based design and manufacturing (CBDM). A feature of CBDM is the ability of service consumers to configure, select, and use individualized resources for the implementation of the product and service ranging computer software to reconfigurable manufacturing systems [6,54–56]. CBDM contributes to a fuller use of the potential of production–distribution networks through rational choice of partners by means of cloud service and centralized flexible managing them in real time under supply uncertainty [54,57]. More recently, Sgarbossa et al. [58] proposed Cloud-based Materials Handling Systems (CMHS) for distribution networks, which included Smart Objects, Material Handling Modules, and Intelligent Cognitive Engines based on cloud-based design. With the help of CMHS, scheduling of the Material Handling Modules can be optimized, increasing the flexibility and productivity of the overall manufacturing system [58]. In the framework of a megapolis, CBDM and CMHS could be implemented by means of the city server. Spatially distributed resources of various enterprises are interconnected in the framework of production and distribution processes of MFMC, the efficiency of which largely depends on the rational choice of partners and sustainable SCM using cloud services.

### *2.3. Smart Sustainable SCM in MFMC*

MFMC gathers mainly SMEs with different production orientations, which determines a wide range of sustainable technologies and production resources used [3,7]. At the same time, the high density of the SMEs in MFMC supposes the presence of enterprises with similar or the same technological capability, which allows them to provide similar products or services, and contributes to fair competition between economic entities based on the transparent market rules [7,18]. The key criteria for the partners selection in the execution of production tasks are lead-time and the sustainability of processes, in line with the "low-carbon logistics" concept [59]. Competitive rivalry between enterprises contributes to the balance of production volumes and the equalization of prices for the same products and services in the framework of MFMC.

A fairly large number of studies have been devoted to the design and planning of production networks, which allow for solving a wide range of problems for optimizing the placement of distributed production facilities, choosing the best network partners, etc. [18,48,53,60]. The problems regarding the design and planning of production networks are quite well studied and are solved using various optimization methods and algorithms [61]. The design of production and distribution processes of MFMC is based on the development of smart sustainable SCM [62–64]. This can be achieved by minimizing traffic flows by reducing empty runs and the compatibility of transported freights in IRTs [7,11,40].

Sustainability in SC is a very important condition in the framework of production and distribution processes of MFMC [3,11,31]. According to Kim et al. [65], the sustainable SC is "a supply chain that not only simultaneously makes a profit and achieves its potential, but it is one that also is responsible to its consumers, suppliers, societies and environments by innovative strategic, tactics, and management technologies". More recently, Sánchez-Flores et al. [27] defined sustainable SCM as "the preservation of the balance that may exist between social responsibility, care for the environment, and economic feasibility throughout the supply chain functions". Various models of sustainable SCM can be used both to assess the sustainability of SCM within a MFMC based on the Triple Bottom Line (TBL) criteria [26], as well as criteria related to minimizing the harmful effects of transport activities on the environment [31,40,66].

Smart SCM means timely delivering/receiving the correct goods to the correct destination using up-to-date information and communications technologies (ICT) for the SC [9,67]. Smart SCM technologies are aimed at building sequences of actions based on the ability to assess situations and solve problems at various levels in the real time [5,68,69]. Cooperation between partners has a great influence on the effectiveness of MFMC processes, and decision support systems should be based on objective information received automatically from monitoring and diagnostic systems [7,40,69]. Therefore, important aspects of smart SCM are the transfer of information between stakeholders, which contributes to the improvement of operational performance, the mitigation the effects of lack of information, and the improvement of risk management under supply uncertainty [67]. Information support for smart SCM can be achieved through the use of blockchain technology and real-time monitoring of IRTs and their freights.

Smart sustainable SCM contributes to increasing the reliability and transparency of SC in terms of procurement, production, inventory management, trade, information exchange, skills development, and opportunities [70–73]. Considering this, in this paper, general aspects of the design and scheduling of production and distribution process of the MFMC are presented.

## 3. Materials and Methods

The design and scheduling of production and distribution processes of MFMC depends on the initial conditions, which are determined by the supplier's contract with the customer: the lead-time for the product, quality of product, its cost, and the supplier's guarantee. The collection of possible process participants is determined by the specified initial conditions, design, and technological documentation of the product. Process participants include production enterprises of the MFMC and their long-distance suppliers, through the CLN supporting intermodal transport. The second group of suppliers includes other MFMC, Recycling, Treatment and Energy Park (RTEP), Industrial and Technology Park (ITP), and Advanced Technology and Education Parks (ATEP). The planning of the production and distribution processes is defined not only by the timing of the production of assembly parts and product components, but also by the capabilities of the logistics and transport system. All deliveries of materials and components to production enterprises, as well as the shipment of finished products and wastes within the agglomeration area, are carried out through the CLNs by means of IRTs, CCs, and cargo vans [7,9,18].

There are challenges associated with this transport system, e.g., the great variety of goods transported, including single or small batches of manufacturing products and different delivery times, which can lead to empty vehicle runs, and an increase in urban traffic and the harmful effects of transport activities on the environment [40,66]. Additionally, processes planning is influenced by the problem of compatibility and perishability factor of freights transported in CCs and the fluctuations in demand resulting in risk of overloading CLNs due to an excessive number of loading/unloading operations. All these challenges are even more complex in the situation of uncertainty in SC. In this regard, there is a need to develop MFMC's planning and distribution model that allows processes not only to optimize, but also to adapt to the requirements of smart sustainable SCM. Figure 1 presents such a model, a visualized material flow system for MFMC SCs analyzed in this study.

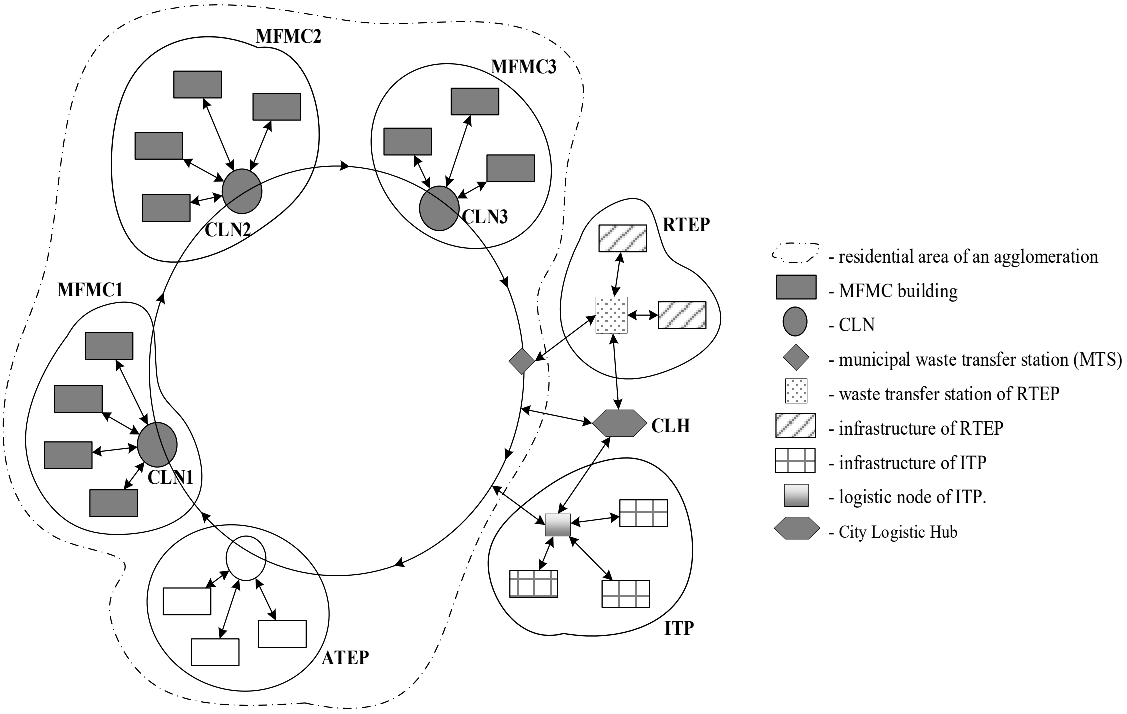

**Figure 1.** Material flow in SCs of the MFMC.

The model presented may ensure that the SC system will work optimally, synchronized, and in a given time cycle. The following assumptions are considered in the model for smart sustainable SCM in MFMC:

- the algorithm of network design and planning of production and distribution processes is implemented in a centralized manner;
- all production and transport facilities and players in the MFMC (enterprises, cargo vans, ATEP, ITP, RTEP, CLN, and city logistics hub (CLH)) are connected via communication channels to a production–service platform [74–77], which means that all data may be handled and stored across the network (Figure 2);
- there is uninterrupted and customized communication between all players within the production and transport system;
- there are no preferences among enterprises performing the same operation;

- an assignment problem solving algorithms requires a matrix as an input to perform optimization.

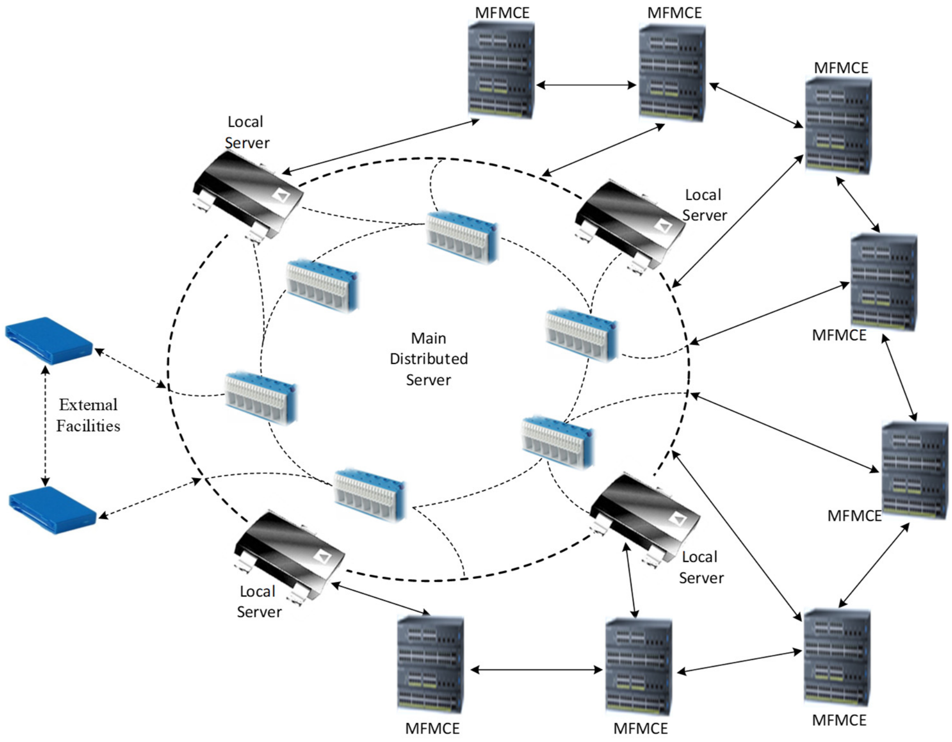

**Figure 2.** MFMC production–service platform.

The core of the presented scheme is a computer server, the key role of which is to maintain a flexible sequencing order and a CLN entity that group together all scattered MFMC enterprises (MFMCEs), into one whole functional system is balancing the workload. This approach can improve the performance of the system by eliminating the situation in which it is overly dependent on specific participants. Weaknesses in the system can lead to disruptions, including the inability to complete certain processes, promised services, or ineffective maintenance due to resource depletion, intermittent downtime, or bottlenecks. The smart sustainable resource management and access to the information required for this is realized through the use of the MFMC production–service platform, which allows stakeholders to optimize resource allocation and provide access to real-time data viewing. In addition, data sharing and computational load are invisible from the user's point of view. This architecture also provides better resistance to system damage.

The most important aspects of the SCM relate to the concept of sustainable network design, taking into account the production processes, resource flow, and the human factor [78]. The integration of SCM systems covers geographically dispersed facilities from which the purchased raw materials, semi-finished products, or finished products come from. In the analyzed case, the authors distinguish between manufactories where the physical transformation of the product takes place, and distribution nodes, where the product is received, sorted, stored, packed, and shipped, but not physically transformed.

SCM refers to integrated planning at the stages of production, procurement, sorting, and transportation of freights, including production waste and warehousing activities, and is associated with the high requirements for the sustainable development of a megapolis. The importance of the SCM of physical materials and products is being amplified by the requirements of the sustainable transport systems and the circular economy, and the need for an integration of production and distribution activities across geographically dispersed SC actors [64]. In a broader sense, the strategy for a conceptual approach of integrated SC planning is more dependent on the intertemporal integration of these activities over resource allocation decisions on medium-term planning horizons, resource acquisition decisions to be taken over long-term planning horizons, and operational planning decisions affecting the short-term execution of the company's business, i.e., defined by environmental, social, and economic aspects [24,25]. Firms faced with the intertemporal integration, also called hierarchical planning, require the preservation of balance that may exist among overlapping SC decisions at various levels of planning. Although it is not yet widely appreciated, intertemporal integration is critical for improving the long-term economic performance of the individual organization and its SC [26].

The design and planning of production and distribution processes for the MFMC is a strategic issue in the management of enterprises that are guided by the goals of sustainable development and operational efficiency. This management issue is common to producers, carriers, and operators, i.e., MFMC enterprises, cargo vans carriers, CLNs, ATEP, ITP, RTEP, and CLH, regarding their role in production and distribution processes. All these actors are important points in the SC covered by a SCM adapted to the needs of a megapolis that want to optimize the SC network and to meet the requirements of sustainable manufacturing [18].

The selection of the best partners of the MFMC production and distribution processes is followed by planning and control of its operation in real time. The planning of production and distribution processes includes defining the delivery conditions for the necessary freights, considering the capacity of IRTs and cargo vans, as well as the compatibility of the transported freights. During execution, the processes are monitored and controlled in real time based on the incoming operational information.

Managing the assignment problem is a main challenge within SCM. Although planning methods are well studied and a variety of solutions are proposed in the literature, the efficiencies of the methods, which do not include uncertainty, obtain inferior results if compared with models that formalize it implicitly.

Experiments have been conducted to illustrate the challenges and advantages of the proposed method for MFMC planning under uncertainty. In this approach, input data are adopted, and the output combination forms a specific matrix. To generate such a matrix, a reduction-based technique, the Hungarian algorithm, could be used [79].

The Hungarian algorithm is an optimization algorithm that may solve assignment problems under uncertainty. Thus, the presented paper discusses the possibility of schedule development that satisfies the requirements in high variety low volume deliveries. In order to use the algorithm, one must provide the lead-time of operations and the possible assignments to fill the lead-time matrix. The classical Hungarian algorithm solves assignment problems with the theorem of zeros elements in matrix. Consecutive steps of the algorithm are performed as follows [80]:

(1) At the beginning, create an efficiency matrix $M_0(n \times n)$ as a representation of the selection problem, i.e., the best production partners selection:

$$M_0 = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nn} \end{bmatrix} \tag{1}$$

where $X$ is the following matrix elements.

(2) Next, subtract the minimum row value from the elements of each $M_0$ matrix row and form a new matrix $M_1$:

$$X_{ij}^1 = X_{ij} - min(X_{i1}, X_{i2}, \dots, X_{in}). \tag{2}$$

(3) Next, subtract the minimum column value from the elements of each $M_1$ matrix column and form a new matrix $M_2$:

$$X_{ij}^2 = X_{ij}^1 - min\left(X_{1j}^1, X_{2j}^1, \dots, X_{nj}^1\right). \tag{3}$$

(4) All zero elements in the matrix are marked with the least number of straight lines. If the number of those lines is equal to the size of the matrix, an optimal selection may be specified according to the location of zero elements within the matrix.

(5) If no, all elements that are not marked with lines will be reduced with the least element that is not covered ($X_{min\_c}$), and those elements that are covered with more than one line will be increased $X_{min\_c}$:

$$\begin{cases} X^3_{ij\_NC} & = & X^2_{ij\_NC} & - & X_{min\_NC} \\ X^3_{ij\_C} & = & X^2_{ij\_C} & + & X_{min\_NC} \end{cases}. \tag{4}$$

(6) A new matrix $M_3$ is formed, replacing the former $M_2$ matrix, and the algorithm is repeated.

The Hungarian algorithm enables a simple but effective way to find the feasible (optimal) solution for the assignment problem. However, in order to achieve optimal production and distribution parameters, upgrading of the proposed method is necessary.

## 4. Production and Distribution Model Formulation and a Case Study

The optimization of production and distribution processes for MFMC can be simplified for the purposes of this study based on the use of the Hungarian algorithm. The proposed model enables selecting the best production partners considering the information available on the MFMC production–service platform, which is based on city and cluster servers. The smart sustainable approach to real-time decision-making based on Big data of the platform allows operators to plan SCM at strategic, tactical, and operational levels in changing transportation conditions.

The main problem when addressing key players, participants in production, and distribution processes, is related to ensuring an appropriate balance between local and global goals. At the same time, the internal structure of the decision-making network should be optimized, taking into account appropriately selected decision criteria. This is the key to increasing the potential of production and offers, its flexibility and product range.

Each of the MFMC included in the agglomeration network consists of enterprises MFMCEs that communicate with each other, taking into account their assignment in the cluster structure. Each of them cooperates in order to achieve their common goal, to execute all production and delivery orders in the best possible way. In order to maintain the sequencing between MFMCEs in production and distribution processes, a special algorithm is needed (Figure 3). The algorithm enables selecting and optimizing dataflows concerning manufacturing the speed, accuracy, and quality of a typical customer order.

Such an algorithm's optimal work requires that all of those MFMCEs exchange production capacities and process data freely. Such a scenario is possible only when a single decision is made with optimal information feedback and a lack of hidden goals. MFMCEs will negotiate the best solutions, but also cooperate to fulfil different operations of the same tasks. Such an approach may improve integration and development of a distributed, but holistic system.

Negotiations performed by the client, who placed the production order, and MFMCEs, are carried out through the MFMC production–service platform taking into account a number of methodological assumptions:

- redundant approach—availability requests may be repeated several times,
- multilateral approach—purpose-set of MFMCEs negotiating with client,
- multicriterial approach—range of goals (minimal price, minimum lead-time, maximum quality, and maximum performance),
- cooperative and competitive approach—MFMCEs operations together to achieve common goals and compete with each other.

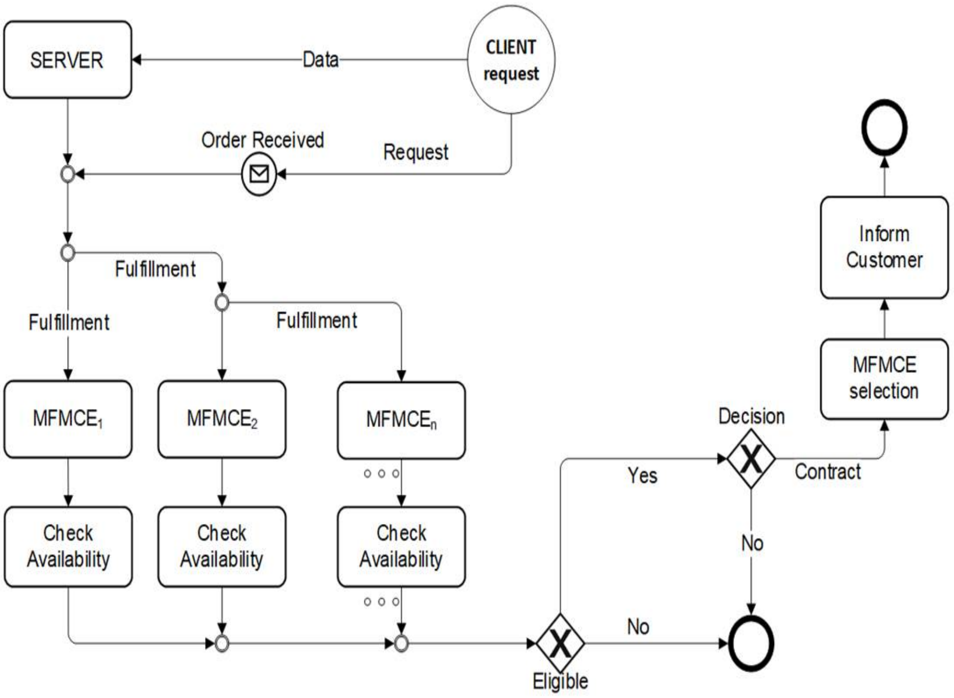

**Figure 3.** Production and distribution network partners selection algorithm.

Negotiations with multiple MFMCEs present opportunities and difficulties. As the system runs, after receiving a client's order, which the system will automatically convert to a production plan containing necessary processes, operations, and resources, each MFMCE checks possibility to work on its own or in cooperation with each other. The MFMCEs prepare their own offers, including possible offers from small production consortia, and negotiate via the MFMC production–service platform. An appropriate dataset is generated by the system as a base for the evaluation and selection of proper MFMCE. One should notice that as multiple MFMCEs may be eligible, i.e., different MFMCEs may be able to complete the same task, an indecision problem may occur. Thus, in order to overcome this problem, the client's multicriteria decision protocols are used.

In order to determine the most optimal MFMCE, key selection criteria (5) for the problem must be defined:

$$c_1, c_2, \ldots, c_q \tag{5}$$

Then, the best choice, which means appointing the best contractors for the production process, should be a minimum or maximum function (8) regarding a combination of selected criteria:

$$F_m\left(c_{1m}, c_2, \ldots, c_q\right) \wedge (1 \leq m \leq q) \tag{6}$$

The above function determines the best solution, when criteria are well known, measurable, and not interrelated. The weight of each criterion should be specified and perform hierarchical analysis, creating a final ranking of solutions. The main principle of such an approach is to perform the following tasks:

- hierarchical representation for available choices,
- specialized evaluation of criteria,
- preference representation for each choice,
- variant classification,
- presentation of the optimal solution.

In order to understand the function of selecting partners to execute a particular production order, simple assumptions that allow to explain the essence of the decision model based on the Hungarian algorithm were made. Only one decision criterion, which is the shortest possible order completion time (total lead-time $t_{LT}$), is assumed. Additionally, it is assumed that only four operation sequences ($OS_1$, $OS_2$, $OS_3$, and $OS_4$) are needed in the production process that is necessary to complete the order. All these operation sequences are to be performed independently by four different MFMCEs, which are integrated into one MFMC. Each MFMCE has a different operational capability and offers a different time to perform each operation sequence. The integrated production and delivery process to be performed by the MFMC within the total lead-time covering the following operational sequences:

- $OS_1$ is time to reach production readiness, $t_1$;
- $OS_2$ is delivery time of the necessary production resources (materials, raw materials, semi-finished products, and components) to the MFMCE, $t_2$;
- $OS_3$ is production time, $t_3$;
- $OS_4$ is the delivery time of the products from the MFMCE to the customer, for example, by means of parcel lockers in CLN, $t_4$.

Taking into account that the second operation step is carried out completely or partially within the first stage, the virtual lead-time can be determined using the following equations:

if

$$t_2 \leq t_1, \tag{7}$$

then

$$t_{LT} = t_1 + t_4 \tag{8}$$

and if

$$t_2 > t_1, \tag{9}$$

then

$$t_{LT} = t_2 + t_4 \tag{10}$$

The following case study demonstrates a simulation-based solution for a chosen general structure of the manufacturing system. In order to enable the simulation and the analysis of the results, a set of sample data has been determined. The table below shows the lead-time for each cross combination of MFMCEs and operation sequences (Table 1).

**Table 1.** Cross combination of MFMCEs and the time necessary for operation sequences.

| | **$OS_1$ [h]** | **$OS_2$ [h]** | **$OS_3$ [h]** | **$OS_4$ [h]** |
|---|---|---|---|---|
| $MFMCE_1$ | 65 | 22 | 11 | 92 |
| $MFMCE_2$ | 77 | 37 | 33 | 91 |
| $MFMCE_3$ | 11 | 104 | 8 | 6 |
| $MFMCE_4$ | 18 | 9 | 34 | 23 |

The goal of the analysis is to minimize the operation lead-time with guaranteed quality of service, as well as to improve the production schedule without significant additional costs. Such a problem may be solved as follows. The first step of the analysis requires the selection of a minimal value from each row of the initial matrix (Table 2).

**Table 2.** Cross combination after row minima subtraction.

| | **$OS_1$ [h]** | **$OS_2$ [h]** | **$OS_3$ [h]** | **$OS_4$ [h]** |
|---|---|---|---|---|
| $MFMCE_1$ | 65 | 22 | 11 | 92 |
| $MFMCE_2$ | 77 | 37 | 33 | 91 |
| $MFMCE_3$ | 11 | 104 | 8 | 6 |
| $MFMCE_4$ | 18 | 9 | 34 | 23 |

The values in the initial matrix are then reduced with the corresponding minima (Table 3).

**Table 3.** Cross combination after reduction by the subtracted row minima.

| | **OS$_1$ [h]** | **OS$_2$ [h]** | **OS$_3$ [h]** | **OS$_4$ [h]** | **RMin** |
|---|---|---|---|---|---|
| MFMCE$_1$ | 54 | 11 | 0 | 81 | (−11) |
| MFMCE$_2$ | 44 | 4 | 0 | 58 | (−33) |
| MFMCE$_3$ | 5 | 98 | 2 | 0 | (−6) |
| MFMCE$_4$ | 9 | 0 | 25 | 14 | (−9) |

The next step is to select a minimal value from each column of matrix and to reduce other values in this column by the identified minimal value (Table 4).

**Table 4.** Cross combination after column minima subtraction.

| | **OS$_1$ [h]** | **OS$_2$ [h]** | **OS$_3$ [h]** | **OS$_4$ [h]** |
|---|---|---|---|---|
| MFMCE$_1$ | 49 | 11 | 0 | 81 |
| MFMCE$_2$ | 39 | 4 | 0 | 58 |
| MFMCE$_3$ | 0 | 98 | 2 | 0 |
| MFMCE$_4$ | 4 | 0 | 25 | 14 |
| | (−5) | (0) | (0) | (0) |

It should be noted that after such a process, there are zero values in each row and column (Table 5). The next step is to cover all zero values with a minimum number of lines (in the example, one vertical and two horizontal gray lines).

**Table 5.** Cross combination with minimum zero lines.

| | **OS$_1$ [h]** | **OS$_2$ [h]** | **OS$_3$ [h]** | **OS$_4$ [h]** |
|---|---|---|---|---|
| MFMCE$_1$ | 49 | 11 | 0 | 81 |
| MFMCE$_2$ | 39 | 4 | 0 | 58 |
| MFMCE$_3$ | 0 | 98 | 2 | 0 |
| MFMCE$_4$ | 4 | 0 | 25 | 14 |

Then, because the number of lines is smaller than 4 (size of the matrix) and the smallest uncovered number is 4, one should subtract that number from all uncovered elements and add it to all elements that are covered by two lines, and again, cover all zero values with a minimum number of lines (two vertical and one horizontal gray lines) (Table 6).

**Table 6.** Cross combination with additional zeros.

| | **OS$_1$ [h]** | **OS$_2$ [h]** | **OS$_3$ [h]** | **OS$_4$ [h]** |
|---|---|---|---|---|
| MFMCE$_1$ | 45 | 7 | 0 | 77 |
| MFMCE$_2$ | 35 | 0 | 0 | 54 |
| MFMCE$_3$ | 0 | 98 | 6 | 0 |
| MFMCE$_4$ | 4 | 0 | 29 | 14 |

There are still only three lines required to cover all zeros, so the previous step should be performed once more. The algorithm requires another iteration of subtraction and adding to fulfil its goals (Table 7).

**Table 7.** Cross combination with all zero lines covered.

| | **OS$_1$ [h]** | **OS$_2$ [h]** | **OS$_3$ [h]** | **OS$_4$ [h]** |
|---|---|---|---|---|
| MFMCE$_1$ | 41 | 7 | 0 | 73 |
| MFMCE$_2$ | 31 | 0 | 0 | 50 |
| MFMCE$_3$ | 0 | 102 | 10 | 0 |
| MFMCE$_4$ | 0 | 0 | 29 | 10 |

Now, because there are exactly four cover lines (which equals the matrix size), it is possible to identify the optimal solution for the problem. The zero values (one for each row and column, Table 8) indicate the exact MFMCEs that should be selected to develop the best possible schedule. It is an optimal assignment and the end of algorithm.

**Table 8.** Cross combination optimal assignment.

| | **$OS_1$ [h]** | **$OS_2$ [h]** | **$OS_3$ [h]** | **$OS_4$ [h]** |
|---|---|---|---|---|
| $MFMCE_1$ | 41 | 7 | 0 | 73 |
| $MFMCE_2$ | 31 | 0 | 0 | 50 |
| $MFMCE_3$ | 0 | 102 | 10 | 0 |
| $MFMCE_4$ | 0 | 0 | 29 | 10 |

Through algorithm iterations, an optimal solution is achieved (Table 9).

**Table 9.** Minimum lead-total time of the operation sequences.

| | **$OS_1$ [h]** | **$OS_2$ [h]** | **$OS_3$ [h]** | **$OS_4$ [h]** |
|---|---|---|---|---|
| $MFMCE_1$ | 65 | 22 | 11 | 92 |
| $MFMCE_2$ | 77 | 37 | 33 | 91 |
| $MFMCE_3$ | 11 | 104 | 8 | 6 |
| $MFMCE_4$ | 18 | 9 | 34 | 23 |

Because there are a finite number of candidate solutions, an enumeration procedure for minimizing the lead time can be developed. For each set of operation sequences, the optimal value of the total lead-time is obtained. The result indicates that the optimal solution for the MFMC production process is a minimal lead-time of 72 h. It can be achieved with following operation schedule: $MFMCE_4$ performing $OS_1$, $MFMCE_2$ performing $OS_2$, $MFMCE_1$ performing $OS_3$, and $MFMCE_3$ performing $OS_4$. All other potential combinations prolong the manufacturing process.

## 5. Discussion

The decision-making model is only one of the tools necessary for the operation of the MFMC production–service platform, which is responsible for the management of all MFMC production and distribution processes. As part of the execution of individual production orders, other tailored tools are needed for communication, data exchange, and process management within the megapolis area and in relation to the long-range SCs to/from megapolis (via CLN, Figure 1). Despite the narrowing of the scope of the analysis and the simplifications applied, the presented model using the Hungarian algorithm demonstrated its potential to solve the problem of partner selection for the execution of the contract by MFMC. Taking into account the goal of optimizing MFMC production and distribution processes, it should be emphasized that it is necessary to expand the presented model to obtain the following functionalities:

- the possibility of multi-criteria evaluation of MFMCEs performing individual operation sequences, i.e., taking into account cost factors (production cost, transport cost, and cost of service guarantees) and quality factors (standard of production technologies, timely service performance, environmental impact, and additional services not covered by the contract);
- the ability to respond to changes in the implementation of production and distribution processes, i.e., delays in deliveries or production, production errors, and changes to the customer's order;
- the possibility of gradual automation of production and distribution processes by replacing humans with robots and remotely controlled devices, autonomous vehicles, and autonomous communication systems within the MFMC production–service platform.

The implementation of each of the above functionalities is associated with a number of challenges of a technical, technological, and organizational nature. Extending the number of decision criteria is possible by expanding the model based on the Hungarian algorithm with modules using heuristic and/or artificial intelligence methods. For example, a dedicated decision module using heuristic methods would be responsible for CC transport management with the use of cargo vans [7,9,31]. This approach allows for defining the criteria for the selection of the best variant for CCs picking [7,35] (Figure 4):

- the deliveries within established time limits (DETL);
- the ensuring the rhythmic operation of internal transport with maximum load (ROIT);
- the realization of full or quasi-full handling of production floors of MFMC building (FQH);
- the freight compatibility in the CCs considering storage and transportation conditions (FC);
- the need to sort freight in the CLN of the cluster after CCs unpicking (SFLN).

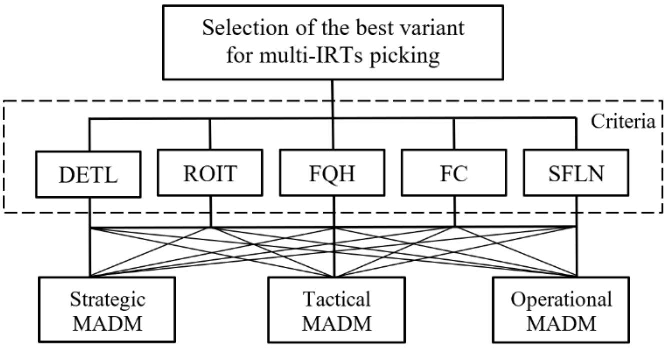

**Figure 4.** Selection of the best variant for CCs picking.

Responding to changes in the implementation of production and distribution processes requires the use of artificial intelligence modules that would allow for the modification of the adopted production or transport assumptions in real time. In response to the gradual automation of production and distribution processes, it is necessary to develop MFMC production–service platforms with machine-to-machine (M2M) technology components: IoT sensors, RFID, Wi-Fi or cellular communication networks, and block-chain databases [81,82]. Autonomous devices and vehicles are not only recipients of commands, but ultimately may be equipped with autonomic computing software to interpret data and make decisions.

## 6. Conclusions

The presented research results are part of a larger research project on the city multi-floor manufacturing, understood as a solution that meets the current economic and logistic needs of megapolises. Previous studies have allowed for the analysis of infrastructural, technological, and organizational requirements, with particular emphasis on the priorities of sustainable development [7,9,40]. The presented research concerns the area of production and distribution process management within the SCs of MFMC. Conditions affecting decision-making in the field of production planning by MFMCEs and accompanying transports within the agglomeration area with the use of the MFMC production-service platform were presented. Assumptions were created for the decision model, allowing for the selection of partners within the MFMC to execute the production order. The adopted assumptions included a centralized management approach, customized communication between all players within the production and transport system, and equal treatment of all service providers. A decision model using the Hungarian algorithm was proposed, which was verified with the use of test data. Finally, the directions of development of the decision model were indicated, defining the necessary functionalities, as well as indicating the technologies and solutions that could be used. Extending the functionality to meet market needs is associated with the expansion of the model with modules using heuristic methods and/or artificial intelligence. The limitation of the Hungarian algorithm when searching for optimal partners for the production and distribution network is that, if the tasks of partner selection are more than workers, some tasks are left not assigned.

Future technical and technological challenges related to the implementation of modern information and communication technologies within the MFMC production–service platform, which would be adapted to the needs of managing production and distribution processes of the MFMCs. Importantly, the discussed processes are dynamically changing, taking into account the quantity and type of MFMCs involved, the potential of the city's transport and logistics network, and the variability of the volume and structure of demand. Organizational challenges are closely related to the automation process and the priorities for flexible use of production and transport potential. Finally, a social challenge is the acceptance of MFMC services by city residents, as without the demand generated by them, the construction and development of this type of system cannot be economically justified.

For future research it is intended to investigate these dependencies in order to clarify the generic usability of the presented approach. Furthermore, it has been planned to develop the conceptual model of MFMC production–service platform with the help of available allocation algorithms and ICT solutions.

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