A city Multi-Floor Manufacturing Cluster

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Multi-floor manufacturing cluster (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. This feature of MFMC promotes business competition, allowing for creating collaborative and networked organizations 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.

Keywords: city multi-floor manufacturing

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][3][4][5][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][13][14][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][18][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].

2. City Manufacturing and Logistics

Kühnle [1] 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 [2][3][4].

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 [5][6]. 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 [5]. 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) [7]. 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 [5][8][9].

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 [10][11][12]. IRTs can also be used as removable buffer drives in sections of automatic lines located on different floors of the MFMC building [13]. 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 [14][15][16]. However, AGVs and AMRs interact with IRTs for the automation of loading/unloading operations [5][16].
IRTs also have a number of features that enable achieving the following goals [5][11][17]

- 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 [5][18].

The future of city manufacturing and logistics in the digital age is linked to the development of smart manufacturing and to production–distribution networks [19][20][21][15].

3. Smart Manufacturing and Socio–Cyber–Physical Manufacturing Systems

Smart manufacturing is a product of the Fourth Industrial Revolution, also known as Industry 4.0 [22], which is based on the wide use of advanced manufacturing solutions, additive manufacturing, information and communications technology, and cyber–physical systems [19][23][24][25]. National Institute of Standards and Technology [26] 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. [27] 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 [28][22] and more recent definitions [19][23][29]. 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 [30].

Kusiak [28] presented the idea of smart manufacturing being based on six pillars:

- increase in the share of innovative technologies in production [19][31];
- innovative materials and technologies for their application [19];
- data, with the focus on "big data" [19][32];
- predictive design engineering with an assessment of production and transport technologies [2][7];
- sustainability of city manufacturing based on the triple bottom line (TBL) covering environmental, economic, and social aspects [33][34];
- resource sharing in a distributed manufacturing environment, and the creation of production–distribution networks [20][1][29].

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 [23][29][35]. Monostori at al. [36] 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 [19]. 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 [19][36][37]. 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 [19][38][39][40]. 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 [38][41]. More recently, Sgarbossa et al. [42] 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 [42]. 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.

4. 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 [33][14]. 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 [14][10]. 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 [43]. 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. [10][30][37][44]. The problems regarding the design and planning of production networks are quite well studied and are solved using various optimization methods and algorithms [45]. The design of production and distribution processes of MFMC is based on the development of smart sustainable SCM [46][47][48]. This can be achieved by minimizing traffic flows by reducing empty runs and the compatibility of transported freights in IRTs [14][20][18].

Sustainability in SC is a very important condition in the framework of production and distribution processes of MFMC [33][20][7]. According to Kim et al. [49], 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. [50] 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 [51], as well as criteria related to minimizing the harmful effects of transport activities on the environment [7][18][52].

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 [5][53]. 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 [54][55][56]. 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 [14][18][56]. 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 [53]. 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 [57][58][59][60].

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