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Green technologies in smart city multifloor manufacturing clusters: A framework for additive manufacturing management

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Abstract

The development of smart sustainable megapolises is associated with the formation of city multifloor manufacturing clusters (CMFMCs) in them directly in the residential area in order to reduce the supply chain from the manufacturer to consumers. Additive technologies (ATs) belong to green technologies because they are considered environmentally sustainable due to less production waste and the ability to reuse of product materials within the circular economy concept. Sustainable development of ATs and additive manufacturing management has become a priority sphere for scientific research, and the use of ATs in the city manufacturing has become any daily reality. Nevertheless, the issues of additive manufacturing management within the CMFMCs have not yet been sufficiently studied. The primary goal of this study was to examine the possibilities of additive manufacturing management in the CMFMCs of the megapolis due to the rational facilities multi-floor layout in production buildings, considering the structure of city manufacturing and business process reengineering related to the needs of the production services market. This paper presents a novel model of facilities multi-floor layout in the production buildings of the CMFMCs, considering the structure of city manufacturing, morphological analysis of the additive manufacturing equipment (AME) used, the balance of material and energy flows under infrastructure capacity limitations of megapolis. The model was verified based on a case study for various options of the floor-by-floor grouping of AME in a building of the CMFMCs. Management solutions for maintaining the flow balance of material, energy and water resources in the CMFMCs are discussed. The results may be useful for additive manufacturing management in an urban environment, taking into account the needs of the production services market in the megapolis.

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1. Introduction

The increase in the number of storeys of buildings in megapolises is associated with limited land resources and the length of transport communications. The formation of city multifloor manufacturing clusters (CMFMCs) in residential areas of the megapolis is aimed to bring closer staff to their places of work, and consumers to manufacturers of consumer goods. The manufacturing embedding in the public communities helps reduce the intensity of urban traffic, relieves congestion on roads during peak hours, and has a positive effect on human health, the efficiency of his work and rest (Westkämper, 2014; Dzhuguryan et al., 2020). The production enterprises in the CMFMCs mainly consist of small and medium-sized enterprises (SMEs), and family enterprises (Ingaldi and Ulewicz, 2020; Dzhuguryan et al., 2020).

Good neighbourship of production enterprise and home in the CMFMCs has become possible thanks to the development of green technologies, among which additive technologies (ATs) occupy a special position due to less negative impact on humans and the environment (Khorram Niaki and Nonino, 2018; Bi et al., 2022; Hegab et al., 2023).

The sustainable development of ATs is aimed at the rapid manufacturing of individual products based on the eco-design concept. Improving living standard through the purchase of innovative green products by the population has led to a revision of approaches to the design and manufacturing of consumer goods in order to ensure better quality, sustainability and price (Bi et al., 2022; Hegab et al., 2023).

The wide range of ATs, production materials and gaseous media used for the implementation of technological processes, different consumption of energy and water resources makes it difficult to find rational solutions for choosing the appropriate modification of additive manufacturing equipment (AME), planning multi-floor layout facilities in the CMFMC buildings, taking into account its structure and sustainable development goals of the megapolis. It is obvious that the CMFMC cannot effectively implement the tasks facing it - quickly and completely satisfy the local population in consumer goods in conditions of shortage of material, energy and water resources. Achieving a balance of material and energy flows in the CMFMCs of the megapolis is one of the priority tasks when planning production by SMEs and family enterprises.

Closing the gaps in additive manufacturing planning and management within the CMFMCs is an important challenge. This study is based on the structure of city multifloor manufacturing analysis, a morphological approach to the formation of facilities multi-floor layout in production buildings, and an analysis of the material and energy flows balance in the clusters of megapolis.

The paper is organized as follows: Section 2 presents a literature review and some key points of the problem of smart sustainable city manufacturing using ATs; Section 3 presents materials and methods for material and energy flow analysis; Section 4 presents the results of the study on additive manufacturing management in the CMFMs; Section 5 discusses and conclusions the research results, taking into account the business process reengineering in the city manufacturing.

2. Literature review

2.1. Smart sustainable city manufacturing

Urban manufacturing is a fundamental component within the framework of a smart, sustainable city (SSC). According to the definition provided by the United Nations Economic Commission for Europe (UNECE) in 2023, an SSC can be characterized as an innovative urban area that leverages Information and Communication Technologies (ICTs) and various other tools to enhance the overall quality of life, optimize urban operations and services, and bolster competitiveness. Importantly, this approach is designed to fulfill the requirements of both current and future generations, encompassing economic, social, environmental, and cultural considerations. Disruptive technologies in the Industry 4.0 era and the Sustainable Development Goal indicators and Key Performance Indicators for SSCs cover various aspects of their development for the quality life support of citizens (Choi et al., 2022; UNECE 2023), including issues related to city manufacturing and supply chains (Lom et al., 2016; Dzhuguryan et al. 2020; Bai et al. 2023). For example, assessments of the city manufacturing and supply chains sustainability are associated with the development and use of innovative green materials, products and goods, equipment and vehicles, processes, renewable energy sources that minimize manufacturing waste and the consequences of transport activities and allow reuse of products and components (including remanufacturing and repurposing) within the circular economy concept (Jabbour et al. 2018; Davydenko et al. 2022, Kuzior et al., 2023; Kusiak, 2023; Alatawneh and Torok, 2023, Andriulaitytė and Valentukeviciene, 2020). Manufacturing and supply chains within a smart, sustainable urban context are built upon the foundations of Industry 4.0 technologies and adhere to the triple bottom line (TBL) principle. The TBL concept comprehensively addresses the environmental, economic, and social dimensions essential for sustainable urban development (Sarkis and Zhu 2018; Kusiak 2019; Sharma et al. 2021; Dudek et al. 2022).

The CMFM refers to smart manufacturing, which is based on the concept of Industry 4.0 (Dzhuguryan et al., 2020; Dudek et al., 2022; Kemendi et al., 2022). The development of Industry 4.0 is associated with conceptual systems and models, and disruptive technologies, as such ICT, human-cyber-physical system, digital ecosystem, cloud-based design and manufacturing, cloud supply chain, cloud-based materials handling system, 5G, IoT, Blockchain, artificial intelligence, digital twins, big data, cloud computing, augmented reality, ATs and robotics (Choi at al., 2022; Ivanov et al., 2022; Kusiak, 2023). Industry 4.0 technologies make it possible to implement a holistic approach to planning city manufacturing and supply chains within the framework of the TBL concept, which helps to improve the efficiency of their management at the strategic, tactical and operative levels (Mishra et al., 2016; Ulewicz et al., 2016; Ivanov et al., 2020). Disruptive digital technologies automatically collect and process production and logistics data in real time in order to make timely and rational decision under uncertainty and rapidly changing market needs (Ingaldi and Ulewicz, 2020; Ulewicz and Mazur, 2019, Tomski, 2023).

The smart manufacturing is characterized by such basic attributes as: cloud manufacturing-as-a-service (CMaaS); sustainability in a broad sense, resiliency, and extreme open orientation for SMEs (Kusiak, 2023). The CMaaS is a service-oriented networked business model that includes physical and digital assets for smart manufacturing implementation and is based on the Industry 4.0 paradigm using ATs, IoT and Blockchain technologies (Rauschecker et al., 2011; Ghobakhloo, 2018; Xu et al., 2018; Kusiak, 2019, 2020, 2023: Ivanov et al, 2022).The features of CMaaS are the following attributes:

i) active collaboration based on digital platform between the manufacturer and the customer at all stages of the product life cycle within the concept of shared economy;
ii) Process-as-a-Service;

iii) Manufacturing Operations-as-a-Service (Rauschecker et al., 2011; Ghobakhloo, 2018; Xu et al., 2018; Hasan and Starly, 2020; Ivanov et. al., 2022; Kusiak, 2020, 2023).

The proposed business model is based on Industry 4.0 technologies, a platform approach within the digital ecosystem and is aimed to shape the CMaaS. It combines all the processes and stakeholders involved in manufacturing and logistics based on the material, financial and information flows of service supply chains (Xu et al., 2018; Kusiak, 2019, 2020, 2023, Ivanov et al, 2022). The CMaaS based on a platform approach allows to dynamically manage the smart manufacturing and supply chain in real time, focusing on customer needs (Ghobakhloo, 2018; Xu et al., 2018; Hasan and Starly, 2020; Ivanov et al, 2022; Kusiak, 2023;). The CMFMC is represented mainly by SMEs distributed within its boundaries and focused on network collaboration within locally distributed open manufacturing (Ingaldi and Ulewicz, 2020; Dudek et al., 2019,2022; Wagner 2021; Kusiak, 2023). In these conditions, the use of a service-oriented network business model based on the CMaaS is relevant. It is also important that such a business model can be part of a network of CMFMCs within a megapolis, which contributes to the expansion of the range of manufactured products and goods in order to better satisfy consumers (Deja et al. 2021, Wagner 2021).

The CMaaS capabilities of have expanded through the use of ATs due to their responsiveness and adaptability in the design and manufacture of configurable products (Ghobakhloo, 2018; Kusiak, 2019; Bi et al., 2022). The efficiency of the CMFMC activity depends on production logistics and, consequently, on the rational layout of AME inside production buildings and in the cluster. The facilities multi-floor layout design are based on the following methods: functional (process-oriented layout), cellular, group technology (product-oriented layout), mixed (Swamidass, 2000; Khaksar-Haghani et al., 2011; Dzhuguryan and Jóźwiak, 2016b; Ahmadi et al., 2017; Groover, 2019; Koumboulis et al., 2023 Kasemset et al. 2023). In CMFM, these methods have been further developed, considering the type of production, which depends on the volume and terms of manufactured products. AME allows to quickly rebuild and focus on both the process-oriented layout, and the product-oriented layout. Thus, with the stationary location of AME in the CMFMC, the type of production organization is constantly changing (Drira et al., 2007). Given the growing trend on the application of ATs in the CMFMC and the lack of a review study on this subject, there was a need to fill this gap by identifying the main features and their classification in order to develop a methodology for facilities multi-floor layout design in a separate production building and in the cluster as a whole. The smart sustainable city manufacturing refers to green manufacturing, which is based on minimizing the impact of technological processes and manufactured products and goods on the environment and the use of renewable energy sources (Westkämper, 2014). ATs and related additive manufacturing can be classified as green manufacturing. ATs are constantly being improved and are increasingly used in the city manufacturing due to environmental friendliness, flexibility, competitiveness for small production volumes and energy efficiency (Khorram Niaki and Nonino, 2018).

2.2. Additive technologies as the basis for smart sustainable city manufacturing

The additive manufacturing according to the ISO/ASTM 52900: 2021 standard is the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". The additive manufacturing techniques according to the ISO/ASTM 52900: 2021 standard are classified as follows: Material Extrusion, Material Jetting, Binder Jetting, Sheet Lamination, Vat Photopolymerization, Powder Bed Fusion, Directed Energy Deposition. The classification of the ATs according to the principles of obtaining products: Stereolithography (SLA), Electron Beam Melting (EBM), Selective Laser Melting (SLM), Direct metal laser sintering (DMLS); Fused Deposition Modeling (FDM), Solid Laser Sintering (SLS), Laser Engineered Net Shape (LENS), Laminated Object Manufacturing (LOM) etc. (Mellor et al., 2014; Khorram Niaki and Nonino, 2018; Mercado Rivera and Rojas Arciniegas, 2020; Rakov and Sukhorukov, 2021; Hegab et al., 2023).

The use of ATs in city manufacturing is continuously growing due to a number of advantages over traditional technologies. Such changes in city manufacturing are dictated by the sustainable development goals of the megapolis, which are headed by environmental, social and economic priorities (Khorram Niaki and Nonino, 2018; Bai et al., 2023; Hegab et al., 2023; Sa et al., 2023). In fact, these priorities are decisive when choosing ATs that meet the sustainable development goals of the megapolis, since they provide the best conditions for CMFM within the framework of CMaaS concepts and the closed-loop economy: green production and pollution prevention, worker health and safety, custom production strategy with sustainable supply chains, selection and supply of materials with the possibility of their recycling, biodegradation and renewal, minimization of production waste, maintainability and maintenance of products (Mercado Rivera and Rojas Arciniegas, 2020; Hegab et al., 2023). However, hybrid additive and subtractive city manufacturing still remains the predominant approach to organizing the production of consumer goods in the residential part of the megapolis (Hegab et al., 2023). The limited use of subtractive city manufacturing is dictated by its impact on the environment and human health due to the presence of production waste in the form of chips, dust and worn tools, cutting fluid, and vibrations and noise (Westkämper, 2014; Hegab et al., 2023).

The growth in the use of ATs in the CMFM is mainly due to SMEs. The use of ATs in family enterprises and households is still insignificant due to the limited production of small-sized modular additive manufacturing equipment, its rather high cost, and the lack of training and educational programs for the use of such technologies by the population. Overcoming these limitations will lead to significant changes in the CMFM within the framework of CMaaS and closed-loop economy concepts, and in the future model of local consumption (Dzhuguryan and Jóźwiak, 2017; Khorram Niaki and Nonino, 2018; Ingaldi and Ulewicz, 2020).

Maintaining a balance of material and energy flows in the CMFMCs is a necessary condition for the implementation of its manufacturing activities in accordance with the sustainable development goals of the megapolis (Ghadimi et al., 2014; Dzhuguryan et al., 2020; Davydenko et al., 2023; Hegab et al., 2023).

The material flows in the CMFMCs are divided into solid, liquid and gaseous (Dzhuguryan and Deja, 2021; Hegab et al., 2023). Solid material flows include flows of solid production materials and products, equipment and solid production waste. Liquid material flows include flows of liquid production materials and products in storage and transportation containers, and flows of liquid production waste, including cooling water. Gaseous material flows include protective gas (e.g., nitrogen, argon) flows, which are necessary for the implementation of individual additive manufacturing processes, and gaseous waste, such as spent protective gas and gas emission (e.g., CO and/or CO2 (Gartner et al., 2015; Bryll et al., 2018; Khorram Niaki and Nonino, 2018; Hegab et al., 2023). The obvious advantage of ATs compared to traditional ones is the smaller flows of solid and liquid production materials and waste due to the absence of such waste as cutting chips and waste cutting fluids (Westkämper, 2014; Khorram Niaki and Nonino, 2018; Hegab et al., 2023).

Flows of energy, water and wastewater after its filtration (if necessary) are allocated to the production enterprises of the CMFMCs by infrastructure enterprises of the megapolis, taking into account the existing capacity limitations, which are determined by their current potential. Distribution of allocated infrastructure capacity to the production enterprises is carried out on a contractual basis, taking into account the facilities multi-floor layout in the buildings of the CMFMCs (Mouzon et al., 2007; Modrzyński and Karaszewski, 2022; Davydenko et al., 2023). The production enterprises of the CMFMCs maintain a balance between consumed and allocated energy and water resources to ensure uninterrupted production activities (Dzhuguryan et al., 2020; Davydenko et al., 2023).

The material and energy flows in the buildings of the CMFMCs depend on the capacity of the available technological equipment and their multi-floor layout, which determines the production logistics of the enterprises (Ghadimi et al., 2014; Dzhuguryan et al., 2020; Davydenko et al., 2023). Therefore, the facilities multi-floor layout problem in the buildings of the CMFMCs is subject to a separate study.

2.3. Facilities multi-floor layout problem in the smart sustainable city manufacturing clusters

The problem of facilities multi-floor layout covers a wide range of tasks to optimize the placement of various objects inside buildings, ships and underwater structures for various purposes (Khaksar-Haghani et al., 2011; Ahmadi et al., 2017). In relation to manufacturing systems, the solution of problems of facilities multi-floor layout is aimed at optimizing the placement of technological equipment and freight elevators in buildings to achieve efficient production logistics. As a result of this optimization, the highest performance of multi-floor manufacturing is ensured while reducing the lead times and work in progress (Drira et al., 2007; Khaksar-Haghani et al., 2011; Ahmadi et al., 2017; Karateke et al., 2022; Liu et al., 2022; Koumboulis et al., 2023). Optimizing energy consumption is also important. For this purpose, it would be possible to adapt Home energy-management system solutions (HEMS) to reduce the carbon footprint (Gualandri and Kuzior, 2023). The overwhelming number of optimizing problems the facilities multi-floor layout is associated with the consideration of a holistic model of the facilities layout of the entire production building at the stage of its design or business processes reengineering existing structures (Ahmadi et al., 2017; Karateke et al., 2022; Liu et al., 2022; Koumboulis et al., 2023). However, it is quite difficult to implement such an approach to the formation of a facilities multi-floor layout in the production buildings of the CMFMC due to the dominance of SMEs with their own vision of the current market conditions. The problem solving a optimal facilities multi-floor layout is also complicated by the fact that SMEs of the CMFMC represent locally distributed productions with the network organization of their activities within the framework of the CMaaS concept (Rauschecker et al., 2011; Dudek et al., 2019, 2022; Ingaldi and Ulewicz, 2020; Deja et al., 2021). In addition, the CMFMCs are located in the large city of megalopolis with a long-established infrastructure of the residential area, in the buildings of which family enterprises are organized using existing freight elevators and green ATs (Khorram Niaki and Nonino, 2018; Dzhuguryan et al., 2020; Dudek et al., 2022). It is obvious that the chaotic layout of multi-floor facilities in such buildings of the CMFMCs will lead to the collapse of manufacturing activity due to a violation of the material and energy flows balance (Ghadimi et al., 2014; Dzhuguryan et at., 2020; Davydenko et al., 2023). The possibility of an imbalance of material and energy flows in each production building of the CMFMC is associated with infrastructure capacity limitations, which are defined by the throughput capacity of freight elevators, energy and water resources of infrastructure enterprises of the megapolis (Dzhuguryan et al., 2020; Modrzyński and Karaszewski, 2022; Davydenko et al., 2023). Resource limitations of megalopolis infrastructure enterprises are defined by their impact on environmental, social and economic aspects of urban environment development (Suh, 2005; Mouzon et al., 2007; Arabi et al., 2017; Mohamad et al., 2022). The formation of a "balanced" facilities multi-floor layout in production buildings of the CMFMC when using a wide range of AME and production materials may be ineffective due to the increased cost of loading-unloading operations, the incompatibility of transported cargo and the increase in empty runs of freight transport (Dzhuguryan et at., 2020; Deja et al., 2021).

Thus, despite the existing studies devoted to the problem of facilities multi-floor layout, there is not enough research related to the rational layout of AME in locally distributed production within CMFMCs. Therefore, it seems justified to conduct a study of additive manufacturing management based on the choice of a rational facilities multi-floor layout in the CMFMC's buildings.

3. Materials and methods

The CMFMC with multi-floor manufacturing buildings and a CLN (Fig.1) is one of the key object of the large city as a residential part of the megapolis whose products and goods are designed to meet the needs of the local population. The activity of the CMFMC is also aimed at satisfying the need for products and services of enterprises and organizations of the megapolis, which include: advanced technology and educational parks (ATEPs), energy parks, industrial and technology parks (ITPs), recycling, treatment and energy park (RTEP); port and logistics facilities (Deja et al., 2021; Dudek et al., 2022). The CLN is the main provider of sustainable and smart services in the CMFMC. The CLN carries out temporary storage of goods, their sorting and dilivery to consumers both inside and outside the CMFMC in accordance with transport lines. The division of material flows into internal and external helps to streamline the freight transport movement in the large city and megapolis (Wiśnicki and Dzhuguryan, 2019; Deja et al., 2021). The main transport and cargo unit of cluster transportation is the intelligent reconfigurable trolley (IRT). Weight and volume of cargo transported by IRT up to 0.5 t and 0.8 m^3. Liquid and bulk cargo are transported by IRTs in appropriate containers, and solid cargo in plastic, paper, cellophane packages or containers. The IRT have the ability to transform for the transportation of various cargo and inform about its location and transported freights in real time using Blockchain technology (Dzhugururyan et al., 2018). A group of IRTs is combined into a city container (CC) for transportation by trucks inside and outside the CMFMC, and by freight elevators of the CLN (Deja et al., 2021; Dudek et al., 2022).

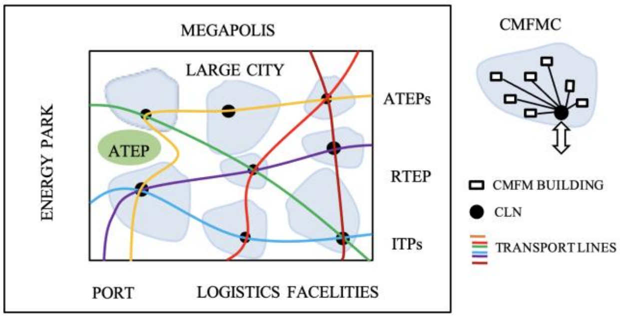

Fig. 1. CMFMC in the structure of megapolis (Deja et al., 2021)

The CLN is the main provider of sustainable and smart services in the CMFMC. The CLN carries out temporary storage of goods, their sorting and dilivery to consumers both inside and outside the CMFMC in accordance with transport lines. The division of material flows into internal and external helps to streamline the freight transport movement in the large city and megapolis (Wiśnicki and Dzhuguryan, 2019; Deja et al., 2021). The main transport and cargo unit of cluster transportation is the intelligent reconfigurable trolley (IRT). Weight and volume of cargo transported by IRT up to 0.5 t and 0.8 m^3. Liquid and bulk cargo are transported by IRTs in appropriate containers, and solid cargo in plastic, paper, cellophane packages or containers. The IRT have the ability to transform for the transportation of various cargo and inform about its location and transported freights in real time using Blockchain technology (Dzhugururyan et al., 2018). A group of IRTs is combined into a city container (CC) for transportation by trucks inside and outside the CMFMC, and by freight elevators of the CLN (Deja et al., 2021; Dudek et al., 2022).

The development of the balance model between the planned production capacities in each CMFMC of the megapolis and infrastructure capacity limitations is based on the fundamental principle of MFA (Material Flow Analyses) – material and energy balance (Ghadimi et al., 2014; Arabi et al., 2017; Dzhuguryan et al., 2020). The materials, energy and water inflow to the floors of each production building is equal to the allocated capacity of freight elevators, electrical and water networks in accordance with the concluded agreements between production enterprises of the CMFMCs and infrastructure enterprises of the megalopolis (Ghadimi et al., 2014; Dzhuguryan and Deja, 2021; Davydenko et al., 2023).

Data collection of using AME and their characteristics are presented in Table 1. The following section presents the results of the study of the structure of smart sustainable city multifloor manufacturing, the morphological analysis of the facilities multifloor layout design, material and energy flow analysis in the CMFMCs under infrastructure capacity.

Table 1. Types of using AME and their characteristics

No.	AT	AME	Occupied area, [m^2]	Material under use	Performance	Power consumption, [kW]	Production waste
1	EBM	Arcam A1	1.7	Metal	55-80 cm^3/h	7.0	Solid
2	SLS	Phenix PXS	0.94	Metal, Ceramic	1-5 cm^3/h	15.0	Solid, Liquid, Gaseous
3	SLM	Sisma MySint100 RM PRO	1.1	Metal	15-18 cm^3/h	1.53	Solid, Gaseous
4	FDM	Ubot s300	0.36	Polymer, Type Filamentary	0.072 kg/h	0.4	Solid
		Raise3D Pro 2 Plus	0.36		24 cm^3/h	0.6	Solid
		Imprinta Hercules Strong 2019	0.25		50 cm^3/h	0.5	Solid
5	SLA	Phrozen Sonic Mega 8K	0.19	Photopolymer	70 mm/h	0.24	Solid, Liquid

4. Results

4.1. The structure of smart sustainable city multifloor manufacturing

The structure of smart sustainable city multifloor manufacturing is shown in Fig. 2 and consists of the following blocks:

1. Fields of action;
2. Structural unit of CMFM;
3. Key structural elements of CMFMC;
4. Classification of CMFM;
5. Facilities multifloor layout design.

The fields of action for smart sustainable CMFM are related to meeting the needs of the cluster's population and enterprises and organizations of the megapolis in innovative green products and services with minimal time and resources in accordance with the circular economy concept (Westkämper, 2014; Dzhuguryan et al., 2020; Deja et al., 2021; Davydenko et al., 2022, 2023).

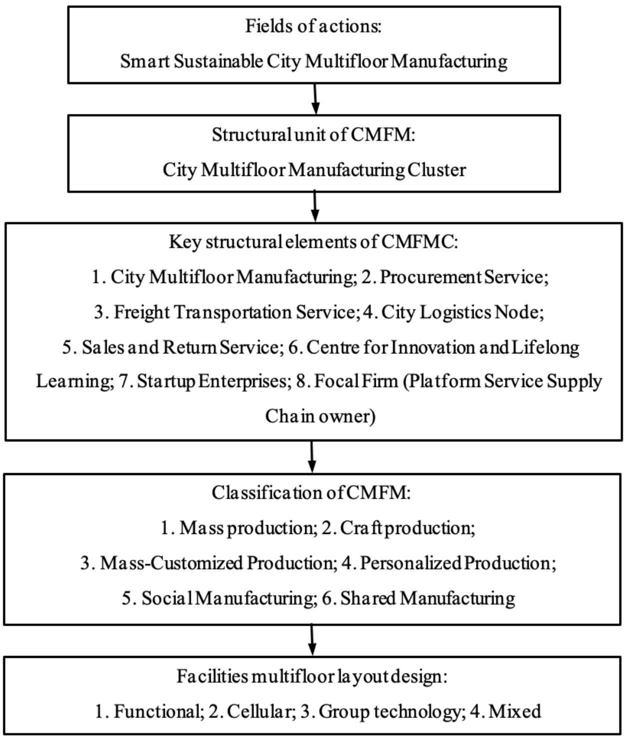

Fig. 2. The structure of smart sustainable city multifloor manufacturing

The CMFMC is a structural unit of the smart sustainable CMFM within the megapolis. CMFMC is a territorial integrated network of production and service enterprises, which are located mainly in multi-floor buildings in the residential area of the megapolis and operate within the framework of the Industry 4.0, smart sustainable city concepts and its following key structural elements:

1. CMFM;
2. Procurement Service;
3. Freight Transportation Service;
4. CLN;
5. Sales and Return Service;
6. Innovation Learning Centre;
7. Startup Enterprises;
8. Focal Firm (PSSC owner) (Deja et al., 2021; Wagner, 2021; Ivanov et al., 2022).

The CMFM as a key structural element of the CMFMC is a network of manufacturing enterprises located in multi-floor buildings of the cluster and operating within the framework of the CMaaS concept and interacting with other key elements of the cluster to meet the consumer's needs in innovative products and goods (Rauschecker et al., 2011; Ghobakhloo, 2018; Kusiak, 2019, 2020, 2023; Deja et al., 2021; Dudek at al., 2022).

The procurement service is a network of service enterprises that provide intermediary services in the CMFMC in accordance with the Procurement-as- a-Service (PaaS) concept, and software on demand based on a cloud-based procurement model within the PSSC to ensure the timely delivery of materials, components, equipment, goods and services for the cluster enterprises (Nicoletti, 2018; Ivanov at al., 2022).

The freight transport service is a network of service enterprises that provide transportation services in the CMFMC in accordance with the Freight Transport-as-a-Service (FTaaS) concept, and software on demand based on a cloud-based freight delivery model within the PSSC (Blanquart and Burmeister, 2009; Dzhuguryan et al., 2018; Wiśnicki and Dzhuguryan, 2019). The cargo flows in the CMFMC can be divided into three groups depending on the volume of one-time transported cargo, which is measured by the number of IRTs as a unit load (Deja et al., 2021):

The 1st group is large-volume cargo, significantly exceeding the holding capacity of the IRT. The transportation of such cargo is carried out by the CC consisting of a picking group of the IRTs. The CCs are transported by freight elevators of the CLN, light e-trucks that deliver cargo to production buildings and the CLN of the CMFMC, and other CLNs and logistics facilities of the megapolis. The recipients of such cargo may be shopping centers, trade fairs, exhibitions, ATEPs, CWTSs, RTEPs, energy parks, ITPs, port, ships etc. (Dzhuguryan et al., 2018; Deja et al., 2021; Zhen rt al., 2021). After unpicking the CCs, sorting the IRTs and their contents in the CLN, the cargo is transformed into the cargo of the 1st and 2nd groups.

The 2nd group is average -volume cargo, corresponding to the holding capacity of IRT. The transportation of such cargo is carried out by the by IRTs without picking them to CC. Transportation of IRTs is carried out by freight elevators in the production buildings of the CMFMC for the purpose of delivery/shipment of goods to enterprises, and by pickups and other vehicles of cargo owners and couriers. It is also possible crowdsourcing or courier delivery of cargo of the 2nd group to the delivery points of the "last mile": shops, ports, ships, post offices, parcel terminals, etc., where they are transformed into goods of the 3rd group (Iwan et al., 2016; D'Amico et al., 2021; Deja et al., 2021; Zhen rt al., 2021; Lyons and McDonald, 2023).

The 3rd group is small-volume cargo, much smaller than the holding capacity of the IRT. Transportation of such goods to customers is carried out by their recipients, courier and crowdsourced delivery using their own vehicles (cars, motorcycles, bicycles, etc.), and public transport (metro, trams, buses, etc.) (Deja et al., 2021; Pietrzak and Pietrzak, 2021; Zhen rt al., 2021; Katsela et al., 2022). As cargo customers, there can be individuals and legal entities permanently (citizens, enterprises and organizations) or temporarily (tourists, sailors, ships, etc.) located in the megapolis (Deja et al., 2021).

According to Deja et al. (2021), the CLN is a unimodal or multimodal and synchromodality logistics facility within the CMFM cluster for CC handling; it is located at the nodal points of the megapolis freight logistics networks and performs the role of a lead sustainability and smart service provider. The CLN is adjacent to shopping centers and provides temporary storage and sorting of IRTs and cargo of the 1st and 2nd groups with subsequent shipment to the customer. The cargo of the 1st group are delivered to customers in the CCs outside the CMFMC with their subsequent transformation into cargoes of the 2nd and 3rd groups and the appropriate mechanism for their delivery. The cargo of the 2nd group from the

CLN are delivered in IRTs to the shopping center and the delivery points, where they are transformed into the cargo of the 3rd group with the appropriate mechanism for their receipt by the buyer (Deja et al., 2021).

The sales and return service offers various sales channels for products and goods produced in the CMFMC, and their after-sales service and return to the manufacturer within a specified period. Sales channels are defined by the sales and return service module of the PSSC in agreement with the seller and freight transport service, from which the buyer chooses the most convenient one for himself, considering which group of goods the purchased product or goods belongs to. The sales and return service module of the platform contains the delivery time, real-time location of the goods, the time of receipt of the goods, database with opinions and suggestions from buyers, analyzes supply and demand, reasons for complaints, and offers channels and for returning products and refund etc. (Deja et al., 2021; Ivanov et al., 2022).

The center for innovation and lifelong learning (CILL) The center is one of the main accelerators for the smart sustainable development of the CMFMC and its competitiveness. The CILL introduces current achievements in the field of ATs and equipment, organizes ongoing professional training and retraining for a wide range of age groups of the CMFMC's people with the involvement of leading scientists, specialists from the region and the world, acquaints the population, enterprises and organizations with new products and startups, organizes consultations, conferences on key issues of cluster activity. Constantly teaches how to use the PSSC and its modules under its constant updating. The main activity of the CILL is carried out through a specialized module of the PSSC and online resources. In the learning process, In the learning process, modern methods of remote, interactive learning, e-learning, self-learning and self-control of the acquired knowledge using training computer programs and films are widely used (Dzhuguryan L., 2018; Deja et al., 2021; Fink et al., 2022; Kuzior et al., 2023). Universities play an important role in the process of spreading and distributing knowledge, as catalysts for co-operation between business, local government and the local community of a smart megapolis (Kuzior and Kuzior, 2020).

The startup enterprises are young enterprises within the CMFMC that create value propositions for consumers in the form of new innovative products and services. The startup enterprises are created with the support of business funds, grant programs and the CILL of the CMFMC center in close cooperation with universities, ATEP, RTEPs, energy parks, ITPs, port of the megapolis (Deja et al., 2021; Wagner, 2021; Magliocca et al., 2022).

The focal firm, as the owner of PSSC, is a orchestrator of the CMFMC's ecosystem, connecting and coordinating the activities of all stakeholders and advocating the value proposition of the ecosystem (Lin et al., 2021; Thomas and Ritala 2021; Dudek et al., 2022) The PSSC is a dynamically changing composition of a wide range of digital services for all actors of the CMFMC, which are provided by ecosystem complementors (e.g., the PSSC provides logistics banking, accounting, tax, innovation, training and learning and other services) (Deja et al., 2021; Lin et al., 2021; Ivanov et al., 2022). The PSSC is also provided the services of external entities of the CMFMC ecosystem: state and regional regulators, ATEPs, RTEPs, energy parks, ITPs, competitors, financial analysts, and the media (Deja et al., 2021; Thomas and Ritala 2021). The PSSC is an integral tool in the organization of CMaaS and allows to create a strong network effect by attracting a large number of participants to the CMFMC ecosystem, who profess the principles of a smart, sustainable city (Ghobakhloo, 2018; Kusiak, 2019; Dudek et al., 2022; Rožman at al., 2023). This contributes to the growth of the sustainable potential of CMFMCs and megapolis as a whole. An important aspect of the effective use of the platform approach in organizing the operations of the CMFMC is the creation of competitive conditions among platform providers, and the use of decentralized platforms based on blockchain technology (Hasan and Starly, 2020; Lin et al., 2021; Tumasjan and Beutel, 2019). The PSSC is a catalyst for the creation of various production and design communities of like-minded people, whose activities erase communication barriers between competing enterprises and contribute to the resolution of problematic issues of production relations in the CMFMC.

The CMFM classification is represented the green production types used in the urban environment: 1. mass production; 2. craft production; 3. mass-customized production; 4. personalized production; 5. social manufacturing; 6. shared manufacturing (Mourtzis and Doukas, 2014; Dzhuguryan and Jóźwiak, 2016a, 2016b, 2017; Lanz and Järvenpää, 2020; Bi et al., 2022; Bouchard et al., 2023). ATs in the CMFMC are used in mass customization, personalization, social and shared manufacturing, which are the main types of city manufacturing within the concept of CMaaS (Rauschecker et al., 2011; Xu et al., 2018; Khorram Niaki and Nonino, 2018; Kusiak, 2020; Lanz and Järvenpää, 2020; Dudek et al., 2022).

The mass production in the CMFMC is characterized by the use of high-performance specialized technological equipment, in particular, production lines and a limited range of standardized small small-sized products manufactured in large quantities, such as fasteners, stationery, haberdashery, fittings, sports and gaming accessories, as well as components for the universities, ATEP, RTEPs, energy parks, ITPs, port etc. of the megapolis (Swamidass, 2000; Dzhuguryan and Jóźwiak, 2016a; Groover, 2019). In the CMFMC, it is possible to use multi-floor (mainly two-floor) production lines with buffer storage and vertical transport such as pipe conveyors and freight elevators. The mass production occupies an insignificant share of the available production areas of the CMFMC (Dzhuguryan and Jóźwiak, 2016a; Ahmadi et al., 2017). Recently, there has been a significant increase in the use of ATs in mass production (Bi et al., 2023). Nevertheless, mass production refers to business-to-business (B2B) model that is not characterized by active interaction with the cosumer and therefore cannot be considered within the framework of the CMaaS concept (Hu, 2013; Kusiak, 2020; Lanz and Järvenpää, 2020). Fundamentally, a CMFMC equipped with AME is capable to manufacture mass products in emergency situations (e.g., medical devices, as it was at the beginning of the COVID-19 pandemic). However, the manufacturing performance and cost of such products are usually inferior to traditional production lines (Khorram Niaki and Nonino, 2018; Advincula et al., 2020).

The craft production, despite its centuries-old history, is still a popular type of city manufacturing. The individual manufacturing in the CMFMC of such goods as clothes, shoes, bags, carpets, jewelry, ceramics, souvenirs and gifts is aimed at meeting the non-utilitarian needs of the population. The realization of the creative potential of artisans plays a significant role in the creation of artistic pieces and luxury goods. By its nature, craft production can certainly be attributed to a unique green production that can quickly respond to changes in market conditions and fashion. The advent of modern tools and ATs has significantly expanded the possibilities of craft production. Nevertheless, the craft production also occupies an insignificant share of the available production areas of the CMFMC (Schortman and Urban, 2004; Mourtzis and Doukas, 2014; Dudek et al., 2022).

The mass-customized production is associated with the manufacture products of customized configuration according to the principle of organizing mass production, based on the optimization of the facilities layout in terms of production logistics. This approach makes it possible to bring the production costs for the manufacture of personalized products closer to the costs of mass production, which allows the manufactured goods to successfully compete in the market of the CMFMC and megapolis (Hu, 2013; Mourtzis and Doukas, 2014; Groover, 2019; Lanz and Järvenpää, 2020; Bouchard et al., 2023). The mass customization provides a basic, usually modular product model and its options, allowing customers to choose from them the combinations of product assembly that suit them. (Hu, 2013; Lanz and Järvenpää, 2020; Bouchard et al., 2023). The mass customization is implemented at an enterprise or at the group of locally distributed enterprises within one or more CMFM buildings of the cluster (Dzhuguryan et al., 2020; Dudek et al., 2022). ATs are increasingly used in mass customization due to the flexibility and mobility of the manufacturing of complex geometry products (Reeves et al., 2011; Salta et al., 2020; Ostertag et al., 2023, Pacana and Czerwińska, 2023).

The personalized production is associated with the production of individual and unique products in agreement with the customer in a timely manner (Hu, 2013; Lanz and Järvenpää, 2020). The personalized production in the CMFMC has received a new development due to the emergence of cyber-physical systems and the PSSC, which, along with the use of ATs, made it possible to carry out online coordination of the product configuration, its characteristics, delivery times, as well as the visualization of manufacturing stages and supply chains (Hu, 2013; Westkämper, 2014; Lanz and Järvenpää, 2020; Dudek et al., 2022; Ivanov et al., 2022; Khorram Niaki at al., 2022). The features of the personalized production, according to Hu (2013) are: "open architecture products, on-demand manufacturing systems, and responsive cyber-physical system". Unlike mass customization, in personalized production, the customer is directly involved in all stages of the life cycle product, including its reuse, as a designer and engineer (Hu, 2013; Kusiak, 2023). On-demand manufacturing systems within the CMFMC are a network of SMEs with a wide range of manufacturing services that provide their facilities, including AME, at an agreed time to the product manufacturer (Hu, 2013; Dzhuguryan et al., 2020; Ingaldi and Ulewicz, 2020; Deja et al., 2021). On-demand manufacturing systems within the CMFMC are a network of SMEs with a wide range of manufacturing services that provide their facilities, including AME, at an agreed time to the product manufacturer. The operational interaction of the CMFM enterprises with the manufacturer and customer of products is carried out through the PSSC of the CMFMC. The result of this interaction is the flexibility and mobility of the provided manufacturing services, aimed at quickly meeting customer needs for personalized products. ATs are key in the development, manufacture and reconfiguration of personalized products at the customer's request with minimal costs (Hu, 2013; Jiang and Ding, 2018; Dzhuguryan et al., 2020; Lanz and Järvenpää, 2020).

The social manufacturing in the CMFMC is based on the principles of personalized production, with the only difference that in social manufacturing the "do-it-yourself "approach prevails and the role of communities increases in the development and production of innovative green products, and locally manufacturing networks using PSSC (Jiang and Ding, 2018; Lanz and Järvenpää, 2020; Dudek et al., 2022;).

The shared manufacturing in the CMFMC is a smart production within the framework of the integration of CMaaS and sharing economy concepts, which, through the PSSC, compares and shares the free reserves of locally distributed enterprises to share orders, resources and manufacturing capacities on-demand (Jiang and Li, 2020; Yu et al., 2020a, 2020b; Dudek et al., 2022; Zhang et al., 2022; Zhu et al., 2023). The development of shared manufacturing is associated with the implementation of Industry 5.0 and Society 5.0 concepts (Leng et al., 2022; Zhang et al., 2022). In this case, the shared manufacturing assume the presence of PSSC that allows the CMFMC enterprises to share their free reserves in real time, including in remote operation mode. Blockchain-based shared manufacturing promotes sustainable and secure interaction between various production enterprises of the CMFMC due such Blockchain Technology properties as: decentralization, transparency, immutability, self-execution (Tumasjan and Beutel, 2019; Zhang et al., 2022; Rožman et al., 2023).

The social and share manufacturing in the total volume of city manufacturing is likely to increase steadily due to the widespread use of ATs in CMFMCs at an affordable cost of AME for the population (Khorram Niaki and Nonino, 2018).

Figure 2 shows possible methods for designing the facilities multi-floor layout in the CMFC. The most widespread in the CMFMC is the functional facilities layout due to the predominance of locally distributed SMEs using ATs (Ingaldi and Ulewicz, 2020; Dudek et al., 2022). Locally distributed SMEs of the CMFMC with a functional facilities multi-floor layout place AME considering the features of technological processes, grouping equipment of the same type in one production building or on its separate floors without specialization in the manufacturing of certain products. This approach reflects: i) the traditional development of SMEs by increasing production capacity through the acquisition of similar equipment; ii) the desire of business owners to ensure high quality of products due to the specialization of personnel and to simplify the maintenance of equipment (Swamidass, 2000; Ingaldi and Ulewicz, 2020; Dudek et al., 2022, Nowicka-Skowron and Ulewicz, 2015). Given the complexity of choosing a rational facilities multi-floor layout in the context of the ATs using in production buildings and in the CMFMC, a method is proposed to support the creation of functional layouts based on a morphological matrix (Zwicky, 1969; Fargnoli at al., 2006).

4.2. Morphological matrix of facilities multi-floor layout design in the CMFMC

The functional facilities multi-floor layout in the CMFMC buildings is defined by the features of technological processes occurring both on existing and newly installed AME, and the features of material and energy flows. The facilities multi-floor layout is preceded by the choice of AME based on the technology assessment, including the study of the market needs for this type of manufacturing services, the possibility of installation and operation in the smart sustainable CMFMC (Dzhuguryan and Jóźwiak, 2017). Only those features of technological processes that affect the facilities multi-floor layout in the CMFMC buildings are subject to consideration. Sorting the features of technological processes, material and energy flows in the morphological matrix for the synthesis of the functional facilities multi-floor layout in the CMFMC buildings is shown in Table 2 (Rakov and Sukhorukov, 2021). As case study, the codes of the floor-by-floor grouping of AME in a 9-floor building of the CMFMC are presented (Table 3) based on combinations of alternatives taken from the morphological matrix.

Table 2. Morphological matrix for sorting the features of facilities multi-floor layout

Function groups	Features	F^1	F^2	F^3	F^4	F^5	F^6	…
F_1	AT	EBM	SLS	SLM	FDM	SLA	DMLS	…
F_2	Working area	Small	Medium	Large				
F_3	Material under use	Polymer	Ceramics	Metal	Glass	Hybrid		
F_4	Initial material type	Solid	Viscoelastic	Liquid				
F_5	Material type & shape	Granules, powder	Sheet	Gel	Filamentary			
F_6	Production waste	Solid	Liquid	Gaseous				

The presented codes for the floor-by-floor grouping of 3 types of AME in the CMFMC building based on the features of facilities multi-floor layout characterize the current technological capabilities of the enterprises located in it and determines the possible of materials and energy flows. Similar codes for the floor-by-floor grouping of AME determine the production capabilities of enterprises of all CMFMC buildings, and a set of such codes for all cluster buildings is its manufacturing potential. The codes for the floor-by-floor grouping of AME are generated similarly for all CMFMCs of the megapolis, which simplifies the search for network partners when organizing virtual enterprises.

Table 3. The codes of the floor-by-floor grouping of AME in a building of the CMFMC

Characteristics of the buildings					Characteristics of the AME			
F	N_f	H_f	T_f	ε_f	Code	Type (No. from Table 1)	Floors	Unit on the floor
1	1	9	0.65	2	$F_1^1 \wedge F_2^2 \wedge F_3^3 \wedge F_4^1 \wedge F_5^1 \wedge F_6^1$	1	1-3	20
					$F_1^2 \wedge F_2^1 \wedge F_3^{2;3} \wedge F_4^{1;3} \wedge F_5^{3;4} \wedge F_6^{1;2;3}$	2	4-6	10
					$F_1^3 \wedge F_2^1 \wedge F_3^3 \wedge F_4^1 \wedge F_5^1 \wedge F_6^{1;3}$	3	7-9	20
2	2	9	1.0	1	$F_1^1 \wedge F_2^2 \wedge F_3^3 \wedge F_4^1 \wedge F_5^1 \wedge F_6^1$	1	1-3	10
					$F_1^5 \wedge F_2^1 \wedge F_3^1 \wedge F_4^3 \wedge F_5^3 \wedge F_6^{1;2}$	5	3-6	100
					$F_1^4 \wedge F_2^{1;2} \wedge F_3^1 \wedge F_4^1 \wedge F_5^4 \wedge F_6^1$	4	7-9	40
3	1	9	0.65	2	$F_1^1 \wedge F_2^2 \wedge F_3^3 \wedge F_4^1 \wedge F_5^1 \wedge F_6^1$	1	1	20
					$F_1^5 \wedge F_2^1 \wedge F_3^1 \wedge F_4^3 \wedge F_5^3 \wedge F_6^{1;2}$	5	2-6	200
					$F_1^4 \wedge F_2^{1;2} \wedge F_3^1 \wedge F_4^1 \wedge F_5^4 \wedge F_6^1$	4	7-8	80
4	1	9	0.65	2	$F_1^2 \wedge F_2^1 \wedge F_3^{2;3} \wedge F_4^{1;3} \wedge F_5^{3;4} \wedge F_6^{1;2;3}$	2	1-3	10
					$F_1^5 \wedge F_2^1 \wedge F_3^1 \wedge F_4^3 \wedge F_5^3 \wedge F_6^{1;2}$	5	4-6	200
					$F_1^4 \wedge F_2^{1;2} \wedge F_3^1 \wedge F_4^1 \wedge F_5^4 \wedge F_6^1$	4	7-9	80
5	2	9	1.0	1	$F_1^3 \wedge F_2^1 \wedge F_3^3 \wedge F_4^1 \wedge F_5^1 \wedge F_6^{1;3}$	3	1-3	10
					$F_1^2 \wedge F_2^1 \wedge F_3^{2;3} \wedge F_4^{1;3} \wedge F_5^{3;4} \wedge F_6^{1;2;3}$	2	4	10
					$F_1^4 \wedge F_2^{1;2} \wedge F_3^1 \wedge F_4^1 \wedge F_5^4 \wedge F_6^1$	4	5-9	40
6	1	9	0.65	2	$F_1^2 \wedge F_2^1 \wedge F_3^{2;3} \wedge F_4^{1;3} \wedge F_5^{3;4} \wedge F_6^{1;2;3}$	1	1-3	20
					$F_1^2 \wedge F_2^1 \wedge F_3^{2;3} \wedge F_4^{1;3} \wedge F_5^{3;4} \wedge F_6^{1;2;3}$	3	4-6	20
					$F_1^2 \wedge F_2^1 \wedge F_3^{2;3} \wedge F_4^{1;3} \wedge F_5^{3;4} \wedge F_6^{1;2;3}$	5	7-9	200

Stage 1. Preliminary grouping of the selected AME in the production buildings of the CMFMC is carried out according to one, several or all features. The preferred option for multi-floor facilities layout is the grouping of AME according to all 6 features. However, it is not always possible to implement such an approach to grouping facilities. Therefore, in each specific case, the defining features of the grouping of AME are selected in order to simplify:

1. Maintenance of the same type of AME, its repair and interchangeability, installation and dismantling, loading-unloading operations (Feature F1) and personnel training (Swamidass, 2000; Dzhuguryan and Jóźwiak, 2016b; Deja et al., 2021).
2. Floor-by-floor facilities layout, considering the size of their working area and the material under use (Features F2 and F3), in which the lower and upper floors are designed for AME, respectively, with large and small working area sizes, with “heavy” (metals, ceramics, glass) and “volumetric” (polymers) products (Dzhuguryan and Jóźwiak, 2016b).
3. Deliveries of the same type of materials and compatibility of transported cargo (Features F4 and F5) in IRTs and CCs with full and quasi-full handling of the buildings manufacturing floors, which significantly reduce the empty runs of the CMFMC's vehicles (Dzhuguryan et al., 2020; Dudek et al., 2022)
4. Shipment of products, solid and liquid production waste (Features F3 and F6) with the provision of full and quasi-full handling of the buildings manufacturing floors (Dzhuguryan et al., 2020; Dzhuguryan and Deja, 2021; Chyr and DeSimone, 2023).
5. Measures to protect against the harmful effects of production liquid and gaseous waste on personnel and the environment (Feature F6), including the personal protective equipment and centralized cleaning before being discharged (Bryll et al., 2023; Chyr and DeSimone, 2023; Hegab et al., 2023).

A simple solution for grouping facilities in the CMFMC according to all 6 features is to locate the same AME in separate production buildings. However, this approach is rarely used because it has significant drawbacks, due to the complexity of implementing a balance between material and energy flows and available production capacities in the CMFMC (Dzhuguryan and Jóźwiak, 2016b; Ingaldi and Ulewicz, 2020; Dzhuguryan and Deja, 2021). Therefore, the most effective solution is a floor-by-floor (1-3 floors) grouping of identical AME into production buildings in the form of a multi-layered cake. Ponderous AME with large working areas for the production of the "heavy" metal products is located on the lower floors, and light AME with small working areas and "volumetric" polymer products is located on the upper floors in the CMFMC buildings. Such multi-floor layout of facilities allows to ensure the load-bearing capacity of building structures and reduce energy costs for cargo delivery in the CMFMC buildings (Dzhuguryan and Jóźwiak, 2016b).

Stage 2. The choice of preferred options for grouping AME in production buildings is carried out taking into account capacity limitations in the transport, energy and utilities infrastructure of the CMFMC (Ghadimi et al., 2014; Dzhuguryan et al., 2020; Gevorkyan et al., 2022; Davydenko et al., 2023). The balance between production capacity and available infrastructure capacity limitations is an indicator of achieving the highest potential of the manufacturing services sector in the CMFMC. A violation of this balance indicates the availability of free production areas or an overabundance of production capacity in the CMFMC. The grouping of AME in the CMFMC with production capacities less than their infrastructure capacity limitations provides for the reservation of production areas for the subsequent development of manufacturing. An excess of production capacity leads to the need for production planning by CMFMC enterprises in accordance with daily schedules for allocating free resources and involves business process reengineering, including operations management based on support the balance of material and energy flows (Ghadimi et al., 2014; Dzhuguryan and Deja, 2021; Davydenko et al., 2023).

4.3. Material and energy flow analysis in the CMFMCs under infrastructure capacity limitations

The main limitations of the CMFMCs infrastructure are related to the capacity allocation of the freight elevators, electrical grid and water supply in the production buildings. The capacity allocation is made by the infrastructure enterprises of the megalopolis to the production enterprises of the CMFMCs on a contractual basis using the PSSC. At the same time, the production enterprises maintain a balance between infrastructure capacity limitations and planned production capacity in each CMFMC of the megapolis (Dzhuguryan and Deja, 2021; Davydenko et al., 2023):

$$\begin{cases} \sum_{k=1}^{s}\sum_{i=1}^{p}(N_i + L_i) \approxeq \sum_{k=1}^{s} P_k \\ \sum_{k=1}^{s}\left(\sum_{i=1}^{p} E_i + \sum_{j=1}^{t} A_j\right) \approxeq \sum_{k=1}^{s} G_k , \\ \sum_{k=1}^{s}\left(\sum_{i=1}^{p} W_i + \sum_{j=1}^{t} T_j\right) \approxeq \sum_{k=1}^{s} C_k \end{cases} \quad (1)$$

where:

$$P_k = \sum_{f=1}^{m} \varepsilon_f N_f H_f / T_f; \quad (2)$$

$$G_k = \sum_{f=1}^{m} E_f; \quad (3)$$

$$C_k = \sum_{f=1}^{m} W_f ; \quad (4)$$

$$p \ll n;\ p + n = m. \quad (5)$$

As case study, consider a megapolis with three identical CMFMs and production buildings (Fig. 3), the initial data of which are presented in Table 3. Figure 3a shows the scheme of the production buildings of the CMFMC with a ground floor, on which the floors with the same type of AME are highlighted in color and arrows show the directions of freight elevators movement. Figure 3b illustrates the scheme of a CMFMC with seven identical production buildings. The capacity allocation of the electrical grid and water supply in each specified production building of the CMFMC with one freight elevator are set to 600 kW/day and 40 m^3/day, respectively, with two freight elevators - 1200 kW/day and 80 m^3/day. The distribution of the allocated electrical grid and water supply capacities in each specified building of the CMFMCs for non-production needs are set to 40% and 60% respectively. The eight-hour shift per day is a working norm for personnel of the CMFMC. When calculating cargo transportation by IRTs in the production buildings of the CMFMC, the actual volume of product packages was taken into account, which in some cases, exceeded the volume of the finished product by 2-3 times. Production waste during additive manufacturing does not exceed 10% of the volume of finished products (Hegab et al., 2023)

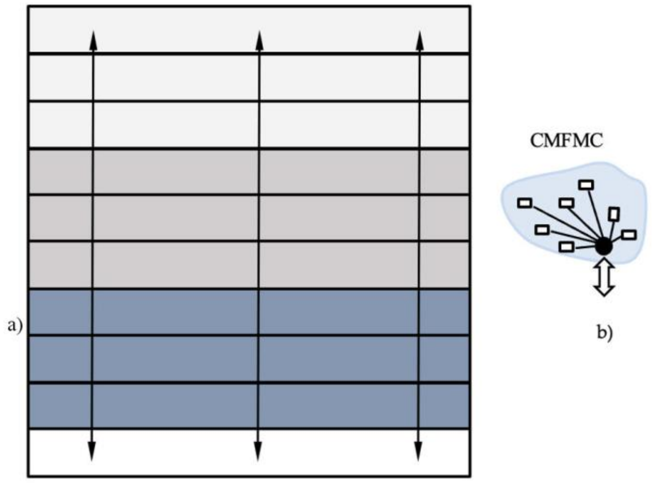

Fig. 3. The scheme of grouping facilities multi-floor layout in the CMFMC's building: a) CMFMC's building (floors with equivale AME are marked in color), b) Seven production buildings in the CMFMC

Table 4 shows the material, energy and water flow through the production buildings of the CMFMCs, taking into account the possible scenarios of floor-by-floor grouping of the AME.

Table 4. The material, energy and water flow through the CMFMCs buildings

Parameters	F							CMFMC	CMFMCs
	1	2	3	4	5	6	7		
$N+L$	0.016	2.9	9.7	5.8	0.029	5.8	11.6	35.9	107.7
P	27.7	18	27.7	27.7	18	27.7	27.7	174.5	523.5
$E+A$	1,042	888	940	1,376	776	1,136	888	7,046	21,138
G	1,200	600	1,200	1,200	600	1,200	1,200	7,200	21,600
$W+T$	54	32	78	73	29	70	83	380	1,140
C	80	40	80	80	40	80	80	480	1,440

The results obtained in this study show the following:

1. The floor-by-floor grouping of the AME has a significant impact on the balance of material, energy and water flows in the CMFMCs of the megapolis.
2. The rational facilities multi-floor layout in the production buildings of the CMFMCs makes it possible to reduce the imbalance of material energy and water flows.
3. The performance of the AME is significantly inferior to subtractive methods of manufacturing products, and first of all, metal and ceramic products (Hegab et al.,2023).
4. At the present stage of development of AME, the performance of AME is significantly inferior to the throughput capacity of freight elevators of the production buildings of the CMFMCs.
5. The manufacturing of metal products using ATs is carried out with low performance, which, along with significant energy and water consumption, limits their use in the production buildings of the CMFMCs.
6. The most effective AT in terms of manufacturing performance, consumption of energy and water resources in the CMFMCs is SLA technology.
7. Water consumption in the case of using AME is relatively low compared to subtractive manufacturing, which is also confirmed by other studies (Faludi et al., 2015; Tavares et al., 2023).

4.4. Managerial Implications

1. The CMFMCs activities in the megalopolis is associated with the constant updating of AME, which is defined by the needs of the manufacturing services market and the emergence of more advanced smart sustainable technologies. In this regard, it is not always possible to ensure balanced flows of materials and energy in the CMFMCs. The imbalance of material and energy flows in each CMFMC is identified by infrastructure enterprises based on a systematic analysis of the daily freight elevators using profiles, and daily power and water consumption profiles in order to reduce them. The analysis of such daily profiles also allows to define the production and non-production flows of materials and energy in CMFMCs, plan the AME operation at less busy times with the allocation of special tariffs, including a feed-in tariff, to ensure flexible and rhythmic operation of production enterprises (Dzhuguryan et al., 2020; Davydenko et al., 2023).
2. The imbalance in the materials and energy flow in the buildings of each CMFMC is revealed by production enterprises and manifests itself in the form of overstocking of finished products, short supply of materials, and lack of capacity to fulfill orders. The elimination of such temporary manifestations of the imbalance in the materials and energy flow in the buildings of the CMFMCs is carried out on the basis of agreements between production enterprises using the PSSC, which result in schedules for the provision of infrastructure capacities to consumers. However, the fundamental solution to such problems is the observance of balance requirements by all enterprises of the CMFMCs (Dzhuguryan and Deja, 2021; Deja et al., 2021).
3. The imbalance preventing of material and energy flows in the CMFMC is possible by organizing two or three shifts of AME operation. When choosing AME for two-three-shift work, they proceed from minimizing harmful manifestations of its operation at night ime, such as lighting, noise, vibrations radiation. One of the requirements for the shipment of products at nighttime is the use of sound-absorbing means when sorting IRTs in transfer areas of production buildings and performing loading-unloading operations.
4. A simplified approach to achieving a balance of material and energy flows in CMFMC buildings is the percentage distribution of infrastructure capacities between groups of floors, in which AME is located on the lower half of the floors with a production capacity of 60% to 70% of the capacity of all enterprises in the building. Such a simplified approach to the grouping of AME is possible both at the initial stage of planning the facilities multi-floor layout, and in the current identification of the reasons for the imbalance in the materials and energy flow in the CMFMC buildings (Dzhuguryan and Jóźwiak, 2017).
5. The imbalance of material and energy flows in the CMFMC is facilitated by the variability of market conditions, which can lead to a reduction in the range of AME. The pursuit of more cost-effective AME reduces the range of manufacturing services provided in the CMFMC. A balanced fleet of AME contributes not only to the promoting of material and energy flows in the CMFMC, but also to the expansion of the range of local products, which contributes to meeting the needs of megapolis consumers.
6. The production enterprises' cooperation with the CILL, aimed at choosing innovative AME, organizing reengineering business processes, and training stakeholders in the ethics of business relationships using the PSSC, contributes to preventing the imbalance of material and energy flows in the CMFMC. The CILL can attract various specialists to solve problems related to the imbalance of material and energy flows in the CMFMC, organize events for the exchange of experience on these issues at the local, regional and international levels.
7. The relationship between lifelong learning and the business process of reengineering in the CMFMCs with the formation of a balanced fleet of AME is an important factor in their sustainable development. The role of the CILL in the sustainable and balanced development of the CMFMC is manifested in the organization: a) cooperation

with leading universities, ATEPs, manufacturers of advanced technological equipment, creators of innovative products and services, external and internal startup enterprises; b) studying the needs of the population, enterprises and organizations in new sustainable technologies and innovative products; c) exchange of professional experience with the best manufacturers; d) improving the qualifications of personnel in various courses; e) obtaining certificates with the right to work on the appropriate equipment; f) advertising of new technologies and innovative products; g) training in the use of innovative products, goods and software products; h) career guidance from schoolchildren to pensioners; i) retraining of cluster employees, providing internship opportunities in other CILLs of the megapolis, and abroad; j) innovative tourism with a combination of knowledge transfer and professional experience of family enterprises from different regions and countries with the study of local attractions, culture and traditions (Dzhuguryan L., 2018). The discussion and conclusions of the results obtained is presented in the next sections.

5. Discussion and conclusions

The framework of additive manufacturing management in the CMFMC of the megapolis are associated to rational grouping and placement of AME in the production buildings, selection of production materials to reduce waste and emissions in order to effectively use the throughput capacity of freight elevators, allocated energy and natural resources. This approach meets the sustainable development goals of the megapolis, which are aimed to implement the circular economy concept: more complete use of extracted resources and manufactured goods, their reuse and recycling, increasing the share of renewable energy sources, reducing production waste and gas emissions (Khorram Niaki and Nonino, 2018; Davydenko et al., 2023; Hegab et al., 2023).

Achieving a rational facilities multi-floor layout in the CMFMC buildings is not always guaranteed to bring positive effects to production enterprises. A lot depends on the needs of the AME in the manufacturing services market. Regularly there are situations in which some AME is overloaded, and the other is idle and does not bring income to the owners. In such a situation, there is a redistribution of material and energy flows to more successful production SMEs.

The production enterprises that have unclaimed AME can solve the problems that have arisen based on studying the needs of the manufacturing services market in other CMFMCs of the megapolis, ITPs, RTEPs, port, and in other regions and countries. The study the needs of manufacturing services market for certain types of AME in various regions and countries is one of the main prerogatives of the CILL of the CMFMC. This study is carried out jointly with manufacturers of such AME who are interested in promoting their products on the manufacturing services market. Obviously, AME manufacturers should advertise the best options for its use, including in the manufacturing of consumer goods. Such cooperation will help to reduce the exchange, resale of secondary AME between regions and countries, and the return of leasing AME to manufacturers. The organization of innovative tourism by the CILLs of the CMFMCs together with AME manufacturers contributes to the rapid business processes reengineering and introduction of innovative products.

The search for innovative products around the world among family enterprises is especially relevant. The transfer of knowledge, technologies and innovative products with high demand by family enterprises to other regions and countries can accelerate innovative tourism. The exchange of experience, knowledge on mutually beneficial terms between family enterprises and the emergence of innovative products in new markets is the best solution to business processes of reengineering.

It is also obvious that the CILLs of the CMFMCs are also involved in regulating the manufacturing services market. Training and retraining of employees to work on new promising AME should be carried out as soon as possible with the involvement of leading specialists of the ATEPs and training centers of AME manufacturers. The continuous process of the knowledge, innovative ATs and products transfer along with personnel training of the production SMEs contributes to balanced manufacturing services market of the megapolis.

This study focused on the design of a framework for additive manufacturing management in smart sustainable CMFMCs based on the analysis of the structure of the city manufacturing, the morphological approach to facilities multi-floor layout in the production buildings and maintaining a balance of material and energy flows in CMFMCs under infrastructure capacity limitations.

A novel model of facilities multi-floor layout in the production buildings of the CMFMCs is proposed, considering the structure of city additive manufacturing, morphological analysis of the AME used, the balance of material and energy flows under infrastructure capacity limitations of megapolis and allowing planning business process reengineering and sustainable development of the city manufacturing potential. The findings provide an insight into the possibilities of using green production technologies in the CMFMCs, taking into account the current potential of AME and the needs of the production services market. Recommended good practices for additive manufacturing management in SSC were also proposed. As a limitation, this paper focuses only on the problem of balancing material and energy flows due to the rational facilities multi-floor layout in the production buildings of the CMFMCs.

The results obtained showed that the development of smart sustainable city manufacturing is limited by the current technical level of AME, which is still inferior to subtractive manufacturing in terms of performance and energy consumption. Subsequent studies will be related to the creation of the facilities multi-floor layout model for hybrid additive and subtractive city manufacturing buildings

Nomenclature

Indexes

K - number of CMFMC in the megapolis, $k = 1, 2, 3, \ldots, t$

I - number of production enterprises in the CMFMC, $i = 1, 2, 3, \ldots, p$

J - number of non-production subscribers in the CMFMC, $j = 1, 2, 3, \ldots, n$

F - number of production buildings in the CMFMC, $f = 1, 2, 3, \ldots, m$

Parameters

N_i - production capacity in the CMFMC of item i (IRTs/h)

L_i - capacity of the production solid and liquid waste generation in the CMFMC of item i (IRTs/h)

P_k - throughput capacity of the freight elevators in the CMFMC of item k (IRTs/h)

N_f - throughput capacity of the freight elevator of item f (IRTs/h)

H_f - number of floors of the manufacturing part of item f

T_f - freight elevator round trip time of item f (h)

ε_f - number of freight elevators of item f (unit)

E_i - production power consumption in the CMFMC of item i (kW/day)

A_j - non - production power consumption in the CMFMC of item j (kW/day)

E_f - capacity allocation of the electrical grid in the building of item f (kW/day)

G_k - capacity allocation of the electrical grid in the CMFMC of item k (kW/day)

W_i - production water consumption in the CMFMC of item i (m^3/day)

T_j - non - production water consumption in the CMFMC of item j (m^3/day)

W_f - capacity allocation of the water supply in the building of item f (m^3/day)

C_k - capacity allocation of the water supply in the CMFMC of item k (m^3/day)

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绿色技术在智慧城市多层制造集群中的应用：增材制造管理框架

關鍵詞
城市多层制造集群 增材制造
设施多层布局
管理
运输

摘要
智慧可持续大城市的发展与在居住区直接形成城市多层制造集群 (CMFMCs) 有关, 旨在减少制造商到消费者的供应链。 增材技术（ATs）属于绿色技术，因为它们被认为在环保方面可持续，减少了生产废物，并能够在循环经济概念中重复使用产品材料。 可持续发展的ATs和增材制造管理已成为科研的优先领域，ATs在城市制造中的应用已成为日常现实。 尽管如此，在CMFMCs内部的增材制造管理问题尚未得到充分研究。 本研究的主要目标是通过合理安排生产建筑物的多层布局，考虑到城市制造的结构以及与生产服务市场需求相关的业务流程再造，研究在大城市的CMFMCs中增材制造管理的可能性。 本文提出了一个新型的CMFMCs生产建筑物多层布局模型，考虑了城市制造的结构、增材制造设备（AME）的形态学分析、材料和能量流的平衡以及大城市基础设施容量限制。 该模型通过对CMFMCs建筑物中AME逐层分组的各种选项进行案例研究来进行验证。 讨论了在CMFMCs中维持材料、能源和水资源流平衡的管理解决方案。 这些结果对于在城市环境中管理增材制造，考虑到大城市生产服务市场的需求，可能是有用的。