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Review

A Conceptual Definition and Future Directions of Urban Smart Factory for Sustainable Manufacturing

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Abstract: Today, megatrends such as individualization, climate change, emissions, energy, and resource scarcity, urbanization, and human well-being, impact almost every aspect of people's lives. Transformative impacts on many sectors are inevitable, and manufacturing is not an exception. Many studies have investigated solutions that focus on diverse directions, with urban production being the focus of many research efforts and recent studies concentrating on Industry 4.0 and smart manufacturing technologies. This study investigated the integration of smart factory technologies with urban manufacturing as a solution for the aforementioned megatrends. A literature review on related fields, mass personalization, sustainable manufacturing, urban factory, and smart factory was conducted to analyze the benefits, challenges, and correlations. In addition, applications of smart factory technologies in urban production with several case studies are summarized from the literature review. The integration of smart factory technologies and urban manufacturing is proposed as the urban smart factory which has three major characteristics, human-centric, sustainable, and resilient. To the best of the author's knowledge, no such definition has been proposed before. Practitioners could use the conceptual definition of an urban smart factory presented in this study as a reference model for enhancement of urban production while academics could benefit from the mentioned future research directions.

Keywords: urban production; smart factory; mass personalization; sustainable manufacturing

Citation: Sajadieh, S.M.M.; Son, Y.H.; Noh, S.D. A Conceptual Definition and Future Directions of Urban Smart Factory for Sustainable Manufacturing. *Sustainability* **2022**, *14*, 1221. https://doi.org/10.3390/su14031221

Academic Editors: Leonor Teixeira, Diogo Correia and João Lourenço Marques

Received: 24 December 2021
Accepted: 18 January 2022
Published: 21 January 2022

1. Introduction

Manufacturing has a considerable influence on the development, wealth, and competitiveness of countries. Factory adaptability to new challenges and trends is a significant factor in retaining or rebuilding a robust manufacturing industry [1,2]. Manufacturing development due to the changing needs of society, markets, and the emergence of new technological capabilities is categorized into several paradigms, i.e., craft production, mass production, lean manufacturing, mass customization, and personalized production. This classification is based on the quantity of production per variant and the product variety. Challenges associated with the new paradigm have been met by the new manufacturing system, which benefited by applying advanced technologies at the time the paradigm was introduced [3,4].

Industrial revolutions—fundamental changes in the manufacturing industry—became possible by applying technologies: water and steam power helped the development of mechanical production, electrical energy enabled the recognition of mass production, and electronic and information technologies advanced automation in manufacturing [5]. Cutting-edge ICT advancement has enabled the development of major technologies, such as the Internet of Things (IoT), cyber-physical systems (CPS), big data, cloud computing, and additive manufacturing (or 3D printing), which provoked a paradigm shift called the Fourth Industrial Revolution or Industry 4.0 [6,7].

Frequently discussed megatrends—major global trends affecting economies, politics, and cultures worldwide—which influence the manufacturing sector are demographic changes (urbanization, population growth, population ageing, ageing distribution), sustainability (climate change, emissions, decarbonization, energy, and resource scarcity, human well-being, market fluctuation, and higher profitability of manufacturing), individualization (product personalization), and human resources (talent shortage or war for talent, unemployment) [8–11]. Improving the efficiency of production processes will be inadequate to meet these megatrends. Urban production could provide solutions to these emergent trends. Improvement in delivery time, minimizing cost while maximizing the degree of personalization by customer involvement in product and service design, shortening the lead time, reduction in transportation emissions, and integration of working and living are mentioned as urban production benefits [12–14].

An urban factory is defined as a production system, a 'factory, within an urban environment'. Being a place of value creation, factories have input and output flows of energy, material, and people. In urban factories, the interdependence of input, output and urban surroundings, and vast customer contributions are undeniable [15]. Considering its diverse potential, urban production is a truly reasonable solution for the abovementioned megatrends. Although, there are some problems, such as spatial issues, environmental impacts, and logistics.

The integration of Industry 4.0 technologies and urban production concepts leads to a new manufacturing paradigm. Product development, business model, and manufacturing process will be transformed because of the customer's involvement in the design process and the interactions of the urban factories with their surroundings on the one hand, and real-time connectivity, CPS, digital twin (DT), big data analysis, artificial intelligence, mixed reality, and additive manufacturing (3D printing) on the other hand.

This study proposes the idea of utilizing smart manufacturing technologies to obtain the greatest benefits from the potential of urban factories while dealing with their challenges. This study consists of five sections. Section 2 presents a brief review of the existing literature on mass personalization, sustainable manufacturing, urban manufacturing, and smart factories. Then, Section 3 covers a literature review on the application of smart factory technologies in urban manufacturing, followed by relevant case studies. Finally, Section 4 presents the urban smart factory's concept, structure, core technologies with relevant key manufacturing systems, and the most expected benefits, followed by the conclusion, which provides essential direction for future research.

2. Research Background

2.1. Mass Personalization

High consumer expectations and market competitiveness have forced nearly all industry sectors to satisfy individuals' needs at a cost comparable to mass production. Compared to other production paradigms, mass personalization is a customer-centric production paradigm in which customers' demands and desires are converted into customized products and services at an affordable cost close to the mass customization satisfactory cost, time, and quality. This is to optimize the trade-off between cost, variety, and quantity [16,17]. Customers will be involved in the design process from the first step. The design will be completed through a co-creation process, while customers' requirements and preferences are well reflected in the product and service, which increases customer satisfaction due to the optimized customer experience. Customers will no longer be product buyers, but rather key entities involved in product and service design [18].

The mass personalization paradigm's goal, scale, production system, and product structure are different from those of other paradigms [4,18].

Due to customer involvement in the design process and demand volatility, unlike mass production and customization, mass personalization cannot depend on standard-specified items that have to be mass-produced and stored. Instead, mass personalization can achieve its goals through an open architecture product platform consisting of three module categories: common, customized, and personalized modules [19]. Modularity is a key enabler for accomplishing personalized production [20]. While common modules may be mass-produced, customized modules can be subdivided based on the frequency of use, and modules with higher rates of use may also be mass-produced. Customized modules with a lower usage rate and personalized modules will be produced on demand [19].

Besides product and service modularity, decentralized manufacturing networks, cellular and flexible processes, and delayed differentiation are other enablers for mass personalization [20,21]. Decentralized and distributed manufacturing systems can offer multiple paths between single manufacturing units for each product, a promising cost-effective and environmentally friendly design option [22]. Under the same personalized product demand, decentralized manufacturing network configurations outperformed centralized manufacturing networks in flexibility and work-in-process [23]. As mentioned above, in the modular production of mass personalized products, common modules and most frequently used customized modules can be mass produced globally. On-demand manufacturing of personalized modules and final production steps, for example, assembly, can be performed in urban factories.

Customer involvement in product design and development—a high degree of personalization—leads to a lack of transparency in diverse dimensions [24]. Owing to a lack of transparency, manufacturers face some important challenges. The major issues that need to be solved are summarized in Figure 1.

Figure 1. Mass personalization challenges due to the lack of transparency.

The manufacturer should create a design framework consisting of interfaces and computational engines. First, a customer-friendly design interface to support customers in creating design conveniently and to demonstrate the results comprehensively and fascinatingly is needed. This adaptive design interface is essential for ensuring customer integration in the design and development process to achieve co-creation and value differentiation [20]. Second, entities are required to assess the manufacturability of the design and find the optimal solution for the trade-off between quality, cost, and lead time. Product configuration, process and material selection, and supply chain and manufacturing routes (decentralized manufacturing networks) are the major parameters to be found. Finally, to support customers in realizing the sustainability of the manufacturing process and the product itself, it is necessary to evaluate the environmental impact (emissions and energy-resource efficiency), and the design of an urban circular economy is necessary. Dwivedi, Ashish, et al. discussed major issues related to Industry 4.0 and circular economy for sustainable footwear production. Some of these issues are due to inadequate understanding of sustainable footwear production, uncertain economic advantage of Industry 4.0 and circular economy application for acquisition of sustainable footwear production, lack of effective means of assessing sustainable footwear production in Industry 4.0 and circular economy, and little understanding of Industry 4.0 and circular economy concepts regarding the introduction of sustainable footwear production [25].

The circular economy is defined as 'a closed-loop system that employs circular processes such as reuse, refurbishing, remanufacturing, and recycling to convert waste into resources' [12]. Design for a circular economy is the overlap of design, innovation, and circular economy ecosystems [26].

Key technologies for mass personalization could be applied in all phases of the product lifecycle, from design, manufacturing, and use to end-of-life and post-use. IoT, DT, and artificial intelligence are necessary for customer involvement, co-design, and personalized manufacturing. Big data, cloud and edge computing, additive manufacturing (3D printing), and mixed reality (MR) would be significantly beneficial.

2.2. Sustainable Manufacturing

Sustainable development is defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [27]. Sustainable manufacturing is defined as the incorporation of manufacturing processes and systems to manufacture high-quality products and services while consuming resources (energy and materials) more efficiently, guaranteeing the safety of all stakeholders (employees, customers, and communities), and reducing environmental and social consequences throughout its entire lifecycle [28]. John Elkington coined the term triple bottom line (TBL), one of the most important approaches of sustainability. It evaluates organizational sustainability by concentrating on three factors: economics, society, and the environment in order to balance the significance of profit, planet, and people [29,30]. As Elkington said, 'The TBL agenda focuses not only on the economic value that they add but also on the environmental and social value that they add—or destroy' [31].

The primary goal of societal sustainability is to promote human well-being (from health and safety to quality of life and ethics). Clean air, water, soil, protocol execution, and eco-balance efficiency are major concerns for environmental sustainability. For the economic dimension of sustainability, the main subjects are increased manufacturing profitability through product and process development, new employment, and large-scale new business opportunities. [1,32–34].

Sustainable manufacturing is recognized and examined at three levels: product, process, and system [32]. To maximize product value, sustainable manufacturing focuses on the 6R approach (reduce, reuse, recycle, recover, redesign, and remanufacture), while green manufacturing principally addresses the 3R approach (reduce, reuse, and recycle) [35]. The recovery stage is concerned with the collection of end-of-life items. The redesign aspect offers environmental consideration by simplifying the future post-use process, whereas the remanufacturing aspect can enhance product performance by conserving natural resources, energy, money, and decreasing waste [32]. The traditional product lifecycle is transformed into the first lifecycle of a product (extended lifecycle; reuse) and its subsequent lifecycles (recycle, reuse, recover, redesign, and remanufacture) [36].

Reduced energy usage, waste removal/reduction, product durability enhancements, elimination of health risks and hazardous dispersion, improved manufacturing quality, improvements in recycling, reuse, and remanufacturing are the main expectations of sustainable manufacturing at the process level [32].

2.3. Urban Factory

Urban manufacturing is an approach that is well adapted to its surroundings, occurs in urban areas, and benefits all parties involved [37,38]. An urban factory is defined as a center of value generation located in a city and categorized as intended and unintended [22]. Proximity to customers, suppliers, and employees, and urban-industrial symbiosis are major characteristics of urban factories, which lead to several potentials cited for urban factories. Customer involvement and co-creation for a higher degree of personalization, connected-continued innovation, shortened lead time and supply chain, reduced value chain and production time and cost, lessened transportation emissions, availability of workforce, especially highly qualified experts, and higher employer attractiveness are some advantages related to the former characteristics of urban factories [12–14,22]. Utilizing urban infrastructure, cooperation with research institutions and universities, exchange of waste heat, excess energy, and recycled materials are potentially related to the latter [10,39–42].

In addition to the advantages, urban factories bring opportunities for new business concepts such as Product-Service-Systems (PSS) and Factory-Service-System (FSS) [38]. The advantages of urban factories are undeniably functional solutions for growing megatrends. The results are summarized in Table 1.

Table 1. Potentials of urban factory as countermeasures for megatrends.

Megatrend	Trend	Potentials of Urban Factory
Demographic Changes	Urbanization Population growth Population ageing	utilize urban infrastructure create local working-class jobs offer part-time jobs for qualified workers opportunities for elderly workforces
Sustainability	Climate change Emissions Resource shortage Human well-being Market fluctuating Higher profitability of manufacturing	lessen transportation emissions exchange of waste heat, excess energy, and recycled materials customer experience/satisfaction/well-being employee well-being community well-being cooperation with research institutions and universities connected-continued innovation
Individualization	Product personalization	develop new business concepts customer involvement and co-creation decentralized production organization Micro-Fabs/Mini-factories
Human Resource	Talent shortage or War for talents Unemployment	availability of workforce especially highly qualified experts collaborative learning/vocational training higher employer attractiveness

Due to their nature, urban factories, located in an urban area, face major challenges, such as spatial issues, regulations, emissions and pollutants, smells, noise and vibration, and logistics and traffic. Limited and lack of affordable spaces, outdated land-use and zoning regulations, political limitations and regulations, planning and construction regulations, high emissions (succeeding the energy sector, the highest emitting sector ahead of the transportation sector), and transportation of materials, components, and products in urban areas are major issues [11,15,43–46].

The United Nations recognizes sustainable industrialization and responsible production as part of the 17 goals established as a worldwide strategy in the Sustainable Development Goals (SDG). Urban factories may have a significant impact on nearly a third of the SDG in urban areas, a strong direct contribution in three of the SDG (8. Decent work and economic growth; 9. Industry, Innovation, and Infrastructure; 12. Responsible consumption and production) and medium direct contribution in two of the SDG (7. Affordable and clean energy; 11. Sustainable cities and communities) [47].

Among the eight resources counted for urban factories, image and appearance both indirectly and directly influence cities. The influence of entities and things on human awareness and their connections is referred to as an image. Appearance influences the identity of a product, building, company, or person [48].

As manufacturers recognize the possible benefits of urban production to meet their challenges, governments realize the importance of plans and strategies to support urban manufacturing. There are several plans in European cities to enhance the conditions for industrial companies and provide assistance for urban production. 'Masterplan Industriestadt Berlin' masterplan of Berlin, 'Regional Sustainable Development Plan' of Brussels, 'The London Plan' of London, and 'Productive City' planning strategy of Vienna should be mentioned [13].

To obtain the greatest benefits from the potential of urban factories and deal with their challenges, smart manufacturing technologies are required in all phases of the product life cycle, and in all interactions between the factory and its surrounding urban area. Integrating the 'Smart Factory' concept into urban production is an innovative process that deals with the emerging megatrends.

2.4. Smart Factory

Industry 4.0 aims to build an extremely flexible manufacturing model of personalized and digital products and services with real-time interaction between people, products, and devices during the production process. In other words, Industry 4.0 aims to create a seamless integration of processes in a smart cyber-physical factory [49,50].

Four subjects are proposed as Industry 4.0 key components: CPS, IoT, IoS, and smart factory (SF); from these key components, six principal designs were derived [51]. Interoperability is a critical enabler of Industry 4.0. CPS and people are linked in Industry 4.0 via IoT and IoS. Standards are a critical success element in the communication of CPS from diverse producers. Virtualization is the CPS's ability to monitor physical processes. Sensor data are connected to virtual plant models and simulation models. As a result, a DT of the actual environment is generated [51].

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The increased demand for personalized products makes it more difficult to centrally control systems. Decisions can be made by CPS on their own through embedded computers. Real-time data collection and analysis are critical factors for decision-making. The IoS provides access to the services of businesses, CPS, and individuals. They can be provided both internally and externally. Finally, different modules of modular systems can be replaced or expanded to flexibly adapt to changing requirements. Consequently, modular systems can be quickly altered in the event of seasonal variations or changes in product quality. Fusion of the physical and virtual worlds is a key component of Industry 4.0 [50].

CPS is defined as 'integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa' [52].

CPS is one of the most important technologies for developing and managing smart factories based on the DT concept [53]. DTs, also called cyber-twins, are accountable for synthesizing future steps to provide self-awareness, self-prediction, self-comparison, self-configurability, self-maintainability, and self-resilience. Self-resilience refers to the ability to manage failures or faults and rapidly return to regular operations [54].

The term 'Internet of Things' refers to a global network of interconnected, uniformly addressed devices that interact via standard protocols. 'Things are active contributors in commercial, information, and social activities; they can interact and communicate with one another and with the environment by sharing data and information perceived about the environment' [55].

The IoS is said to be the next generation of Internet-based services. This concept outlines an architecture that leverages the Internet to deliver and sell specialized services [56].

Addressing vertical integration and networked manufacturing systems for smart production, the SF is a key component of Industry 4.0 [57]. Cloud manufacturing, advanced manufacturing, ubiquitous manufacturing, digital manufacturing, and SF are interchangeably used in many countries [58]. There are more synonyms for SF, such as ubiquitous factories, factory-of-things, real-time factories, intelligent factories [59].

The SF is defined as ‘a Factory that context-aware assists people and machines in the execution of their tasks.’ There is a paradigm shift to decentralized production processes, and by modular simulation of manufacturing processes, such as product design, planning, engineering, production, and services, these processes are controlled intelligently, interdependently, and simultaneously [2,51]. The SF could also be considered as an actual implementation of CPS based on broad and in-depth use of information technology in a manufacturing closed-loop system, wherein there are smart objects in the center of the control loop. Smart objects have five major capabilities: computing, communication, control, autonomy (making decisions by themselves while no other entities have direct influence) and sociality (negotiate based on a common set of knowledge and of rules) [48]. CPS, flexible, reconfigurable, and adaptive production processes are major parameters included in SF definitions [51,55,59,60].

Modularity, interoperability, decentralization, virtualization, and real-time capability (responsiveness) are the design principles of SF [2]. Their major characteristics are real-time data and information exchange among all parties, co-design, flexibility, factory transparency and optimized decision-making, new planning methods for factories, creating value from big data collected, creating new services, remote monitoring, proactive maintenance (preventive and productive maintenance), connected supply chain, and energy management [61].

Nine technological advancements are counted as pillars of Industry 4.0: Big data and analytics, autonomous robots, simulation (leveraging real-time data to mirror the physical world in a virtual model; DTs), horizontal and vertical system integration, industrial IoT, cybersecurity, cloud, additive manufacturing, and augmented reality [62,63].

3. Literature Review

Recently published review studies on urban production show that the potential limitations of urban production systems are presently the main subjects of study, and there is a gap between the realization and modelling of the essential interdependencies, and connections between the involved (sub-) systems, as well as technical solutions that contribute to this goal [22].

Some research on urban production partly covers contributing technologies, especially Industry 4.0 and SF technologies, yet there exists a gap in the full integration of SF technologies into urban production. Akpolat et al. introduces application of smart technology such as CPS and IoT in an urban factory and addresses the interoperability characteristic [64].

This study proposes an Urban Smart Factory (USF) concept divided into four major parts: concept, structure, core technologies with the relevant key manufacturing systems, and benefits. This section summarizes the literature review focusing on SF technologies and manufacturing systems linked to urban production. In addition, several case studies associated with the abovementioned four major points of USF are listed.

3.1. Application of SF Core Technologies and Key Manufacturing Systems in Urban Production

Among SF technologies, CPS, 3D printing, and MR are probably the most cited technologies for optimizing urban production potentials. Herrmann et al. argued that CPPS (cyber-physical production systems) are product personalization enablers, which also contribute to minimizing the negative impacts of urban production. In addition, CPPS can support robust or resilient manufacturing processes [22]. Herrmann et al. regarded CPS as corresponding to the bio-intelligent principle from the ‘biological transformation’ concept. CPPS participate in control processes and track symbiotic relations between the production system and its surroundings [38]. Tötzer et al. considered CPS, human-robot collaboration, and cloud solutions as technologies that provide opportunities for urban manufacturing [43]. Lentes et al. developed a roadmap for companies to guide their evolution to urban manufacturing. This roadmap has seven perspectives, with five steps each. The final state of the fourth perspective (manufacturing) is self-organization through CPS that control product flow and manufacturing parameters [44]. Singh et al. mentioned

Wittenstein bastian that attempted to develop a future gearing system through integrated CPS. The participation of Wittenstein bastian in the public-funded project, "CyProS—cyber-physical production systems", resulted in productivity and flexibility enhancement through CPS and intelligent systems [46].

Herrmann et al. clarified that the rising productivity of additive manufacturing and 3D printers is a potential technical breakthrough for urban production. The application of 3D printing by the U.S. Department of Veterans Affairs (VA) in the production of medical products, such as hand orthotics in hospitals, is an exemplary approach [22]. Tsui et al. argued, through a literature review, that since 3D printed products use fewer materials, they can decrease emissions [12].

Herrmann et al. posited that MR could improve workplace quality, recruiting within a factory, and transparency in production processes and environmental consequences [22]. Pinzone et al. categorized MR as a "silent teacher" who supports the operator's training to improve their abilities continually and, as a result, makes the factory more competitive [65,66].

Lentes et al. considered the decentralized manufacturing approach as the final state of the second perspective (i.e., factory) of the proposed roadmap for urban manufacturing. It involves one or more factories manufacturing customer-neutral pre-products (i.e., common and optional modules) focusing on economies of scale, and urban factories devoted to the production of customer-specific goods (e.g., personalized modules) and final assembly [44]. Juraschek mentioned that results of the life cycle evaluation show that decentralized manufacturing methods can have a lower environmental effect under suitable conditions than centralized mass production systems [67,68]. Further, Juraschek stated that distributed manufacturing systems in urban systems support the realization of the circular material flow concept, which reduces the environmental impact of products [69].

Modular and flexible factory structures, with three layers, CPPS, cyber-physical production module (CPPM), and CPS support personalization through smaller batch sizes with capability to manufacture larger varieties. Britel discussed that in a human-centered, decentralized, and modular production environment, workers must interact with machines in a standardized and adaptable manner. Condition monitoring of CPPM is enabled through the asset administration shell (AAS) approach [70].

3.2. Case Studies

- Adidas—Knit for you (Germany)
  Concept: Production of personalized knit at a shopping mall (Berlin)
  Structure: User-friendly design interface
  Technology: 3D scanning and real-time simulation
  Benefits: Affordable personalized product, shortened design and production time, and supply chain
  Personalization is one of the most critical aspects of the USF, as presented in the previous section. Adidas' 'Knit for you' pop-up store in Berlin is an appropriate case to highlight this concept. Customers directly designed their sweaters, while a 3D scanner was utilized to find the customer's exact fit, and then the sweater was made in the store, and customers took the product home on the same day [71,72].
- Close to the customer (CTC) mini-factory (Italy)
  Concept: Production of personalized, sustainable furniture at a shopping mall
  Structure: User-friendly configurator
  Technology: IoT, cloud, modular product design, real-time update of production data monitoring
  Benefits: Customer satisfaction, shorter supply chain, reduced waste, image, and appearance shared have impressed a high number of visitors of the shopping mall.
  Another USF case study focusing on personalization is the 'Close to the Customer (CTC) mini-factory' scenario, in which personalized furniture is produced behind a glass panel in a shopping mall. A user-friendly configurator supports customers to

personalize furniture preferences. Predefined parametric portfolios of products and functional constraints of the mini-factory are drivers of furniture design [36,73].

- DigiPlex (Sweden)
  Concept: Resource efficiency—reusing waste heat for heating residents in Stockholm
  Benefits: Environmental sustainability
  Environmental sustainability is primarily concerned with energy and resource efficiency. In addition to energy monitoring, one significant way of improving energy efficiency is that companies supply electricity and heat to the cities from the waste heat of industrial processes. DigiPlex (data center operator) and Stockholm Exergi (heating and cooling supplier) agreed to reuse the waste heat of the data center for heating 10,000 modern apartments in Stockholm, Sweden [43].
- Alpha Biofuel (Singapore)
  Concept: Material and resource efficiency—reusing waste cooking oil as biofuels
  Benefits: Environmental sustainability
  Resource efficiency usually improves by minimizing waste through design and process improvement. One innovative way for resource efficiency in urban manufacturing is to use available waste materials as resources. Alpha Biofuel Pte Ltd.(Singapore 637601, Singapore) produces and sells small-scale refineries to convert cooking oil into biodiesel. The National University of Singapore has practiced recycling used cooking oil from different faculties into biodiesel to fuel university cars [38].
- Wittenstein bastian—Future Urban Production (Germany)
  Concept: Environmental, Social, and Economic Sustainable Production in Fellbach
  Technology: Smart Sensors, IoT, CPS
  Benefits: Improving workplace well-being, low noise and emission, and sharing of residual heat with surrounding urban areas
  Wittenstein bastian is a USF located in Fellbach near Stuttgart. People, machines, and products communicate through an intelligent CPS. Wittenstein considers employees fundamental to all production processes. To increase employees' productivity and flexibility, tailored information is provided to them at the right time. Low noise and emissions, and energy efficiency for residential neighborhoods that contribute to the local community by using residual heat during production as district heating are other company attributes [46,74].
- Factory-as-a-Service (South Korea)
  Concept: Multiple connected micro-factories for resilient personalized production
  Structure: Factory-as-a-Service (FaaS) cloud platform, FaaS manufacturing operation platform, FaaS monitoring and control platform
  Technology: DT and CPS, 3D printing
  Benefits: Real-time monitoring of the present, tracking of past information, and operational decision-making to support the future reduction of cost and production inefficiencies
  Distributed and modular manufacturing systems contribute to the first pillar of USF, personalization, and bring solutions for major issues such as spatial limits and logistics. FaaS, an open manufacturing service, consists of a multiple connected micro smart factory (CMSF) developed with DT application to achieve logistical advantages and ensure the efficiency of manufacturing through real-time monitoring, tracking the past, and decision-making support by predicting the future [75,76]. To achieve resilient production control, there are core functional requirements: action selection, KPI measurement, adjustment through modular production systems, DT applications, and reinforcement learning [76,77].
- Nobilia—Manufacturing by Wire (Germany)
  Concept: Production of personalized kitchens
  Structure: Nobilia Kitchen Configurator
  Technology: Smart Sensor, IoT, CPS, decentralized decision-making

Benefits: Optimizing the degree of personalization, shortening the manufacturing time, reducing waste materials and energy consumption, and practical production of products in a wide variety and high volume.
Nobilia, the German kitchen manufacturer, produces 2,800 personalized kitchens every day, with 14 million possible variations. This is feasible through CPPS. Nobilia introduced a production system called 'Manufacturing by Wire' to secure competitiveness through in-house production in Germany. By implementing SF technologies, such as IoT and CPS, mass personalization was achieved. SF attributes, such as decentralized and autonomous decision-making, significantly reduced the production time. Each raw material was attached to a barcode containing the customer's order. Material-machine and machine-machine connections, through IoT, made it possible to produce different types of furniture in one production line. Through SF realization, quality is maintained, waste materials are minimized, and production costs are significantly reduced [78,79].

- Volkswagen—Transparent Factory (Germany)
  Concept: Production of personalized autos in a fully transparent production line
  Benefits: Optimizing customer experiences
  In addition to personalization, developing a new business model such as servitization is important for USF. In this regard, Volkswagen's 'Glass Factory', opened in December 2001 in Dresden, is a brilliant example. The production facility, equipped with soundproof windows, is grounded on an entirely new approach that blends industrial vehicle production and high-quality workmanship under visible conditions. Purchasing has transformed into a personalized matter in which, customers can not only choose and order the vehicle, but also monitor the manufacturing in real-time. As a result, the emotional ties between customers and the brand are reinforced. The 'Transparent Factory' also establishes new norms as a service center where the manufacturing process is displayed as an attraction. The image and appearance of an urban factory are well reflected [80,81].
- Hyundai Motor Group—E-FOREST (HMGICS at Singapore)
  Concept: Sustainable and resilient production of personalized mobility products
  Structure: Customer interface for personalized design
  Technology: Smart sensor, IoT, DT and CPS
  Benefits: Optimizing customer satisfaction, improving workplace well-being, sharing infrastructure for global research and development experts, and collaboration with local communities
  Recently, Hyundai Motor Group announced the E-FOREST as 'an innovative smart factory of Hyundai/Kia Motors that would connect people, nature, and technology into one.' The E-forest seeks manufacturing system innovation by naturally connecting everything to create customer value. The E-Forest pilot plant was launched in Ulsan in January 2020. E-Forest strives to achieve three values: auto-flex, intelligence, and humanity. Auto-flex is about the flexibility and responsiveness of the system that comes by introducing a new and advanced automated manufacturing technique. Autonomous systems are realized by using artificial intelligence and big data to achieve self-resilience. In addition to all data from systems within the factory, information from beyond the facility is collected and analyzed to optimize consumer satisfaction. Finally, workplace well-being is of great value and is maximized in the E-Forest. Two examples are of wearable robots that aid employees in the manufacturing line (Vest Exoskeleton) and a knee-supporting robot (chairless exoskeleton) [82]. After the E-Forest pilot plant launched domestically, the Hyundai Motor Group announced the establishment of the Hyundai Mobility Global Innovation Center in Singapore (HMGICS). It was introduced as a manufacturing hub hosting a thriving ecosystem of researchers, technology, training providers, and future factories. HMGICS, as a complete model of E-Forest, is expected to open in the second half of 2022. As a customer-centered smart mobility environment, personalization and mobility services maximize customer well-

being. Human-centered digital transformation improves workplace well-being. As an urban factory located in the center of Singapore, it not only cares about environmental sustainability (through renewable energy use and resource efficiency) but also shares infrastructure for global research and development experts while expanding collaboration with local research institutes and universities [83,84].

We have briefly introduced several cases that demonstrate personalization, sustainability, and resilience through SF technologies; some examples completely match the urban production concept. The last example is probably the closest practice to the USF idea presented in the next section. The case studies are summarized in Table 2.

Table 2. Summary of case studies.

Case	Type	Sector	Description
Knit For You	Practical Business	Sportswear (Adidas)	Personalized knit
CTC	Research Paper	Furniture Manufacturing	Personalized furniture
DigiPlex	Practical Business	Data Centre	Reuse of waste heat
Alpha Biofuel	Practical Business	Refinery	Recycling of used cooking oil
Wittenstein	Practical Business	Engineering (gear systems)	Workplace well-being, energy sharing, Noise and emissions reduction
FaaS/CMSF	Research Paper	Manufacturing	Personalization, resilience, solution for spatial limits
Nobilia	Practical Business	Kitchen Manufacturer	Product personalization, Sustainability
VW T-Factory	Practical Business	Automotive Industry	Service personalization, Sustainability
E-Forest HMGICS	Practical Business	Automotive Industry	Service and product Personalization, sustainability, resilience

4. Urban Smart Factory

This study proposes a conceptual definition for an emerging manufacturing paradigm such as USF, wherein product development, business model, and manufacturing processes are quickly transforming. Product/service personalization and business models focused on sustainability and resilience are major aspects, while SF technologies are enablers for this manufacturing paradigm.

4.1. Concept

As mentioned previously, urban production has several potential advantages and disadvantages. Optimizing potential benefits and minimizing the drawbacks of urban production through SF implementation will bring solutions for the aforementioned megatrends such as individualization, climate change, pollutant emissions, energy and resource scarcity, and human well-being. USF also has a strong interrelationship with the smart city concept.

A smart city is defined as 'a well-defined geographical area, in which high technologies such as ICT, logistic, energy production, and so on, cooperate to create benefits for citizens in terms of well-being, inclusion, participation, environmental quality, and intelligent development'. Other expressions to explain similar concepts are intelligent city, digital city, and technology city [85]. The major components of a smart city are the smart economy (industry), smart people (education), smart governance (e-democracy), smart mobility (logistics and infrastructure), smart environment (sustainability and efficiency), and smart living (security and quality) [86]. The USF concept shares several correlations with all the six components of the smart city. There is a direct relationship between USF and the smart economy. USF also influences smart people—'a combination of education, lifelong learning, ethnic plurality, and open-mindedness' [87]—especially over education and lifelong learning dimensions. Smart mobility, environments, and living overlap with the USF concept.

By word-by-word lexical meaning, USF is an SF located in an urban area. However, the USF introduced in this study represents a broader concept. We define USF as

> "a factory in which product/service personalization, employee well-being, collaboration with local communities, sustainability, and resilience are the primary objectives to be achieved through the utilization and realization of the SF".

First and most importantly, USF is a human-centric factory in which: (1) customer involvement in the design process is as high as possible, (2) employees are regarded as assets, and (3) close collaboration with local communities is a high priority. The second characteristic of the USF is sustainability in all TBL dimensions: environmental, social, and economical. Finally, its third feature is the ability to manage internal difficulties such as equipment failure or faults and rapidly returning to regular operations (self-resilience) and bear or recover swiftly from external adversities. The key USF characteristics are listed in Table 3.

Table 3. Key characteristics of USF.

Characteristic	Category	Description
Human-Centric	Customer	Personalization of product/service through co-creation
	Employee	Workplace well-being, lifelong education, etc.
	Communities	Close collaboration, education, open innovation, etc.
Sustainable	Environmental	Minimizing emissions/pollutions, Resource and energy efficiency
	Social	Customer/employee/citizen well-being
	Economy	Value creation, new business model development
Resilient	Internal adversity	Wrong decision-making, equipment failure, strike, etc.
	External adversity	Political issues, natural disasters, regulations, etc.

Co-creation for product/service personalization, maximizing employee well-being, minimizing the environmental impact of the production process and the product itself, optimizing resource and energy efficiency, maximizing collaboration with local communities, and realizing the design-for-circular-economy are USF attributes, which altogether consider the mutual relationship between USF and surroundings, as demonstrated in Figure 2.

Based on the presented definition for USF, our model consists of four main pillars: personalization, sustainability, resilience, and SF. Among the five primary goals stated for the USF, employee well-being and collaboration with local communities are included in the social dimension of sustainability.

A high degree of personalization can be achieved through design co-creation. To this end, the manufacturer shall provide the customer with a design interface to expand the customer's role from choosing among limited options to designing the product as per preferences. As mentioned previously, modular product design is a feasible method for co-design implementation.

Personalized modules designed by customers affect manufacturing feasibility, quality, delivery time, price, and sustainability. A design platform is needed to deal with these five parameters.

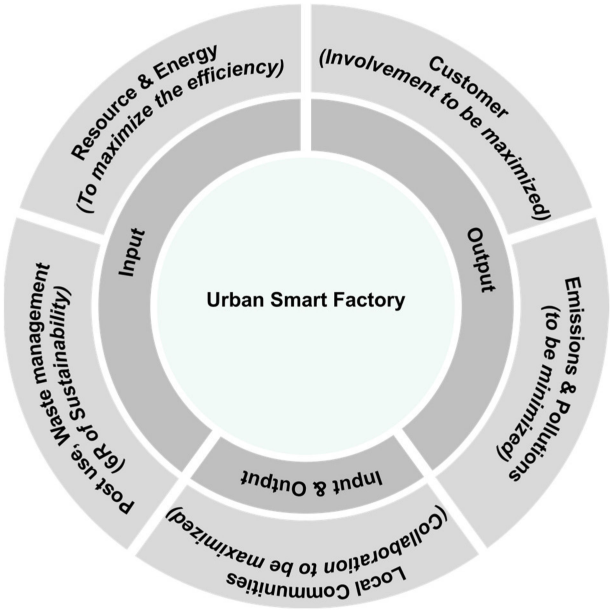

Figure 2. USF and stakeholders/surroundings mutual relationship.

Sustainability in the USF concept is considered for all three dimensions: environmental, social, and economical. In terms of product and process, environmental sustainability, resource and energy efficiency, zero-emission, zero-pollution (noise, vibration, smell), and design for a circular economy are the main parameters to be attained.

Citizen well-being is the ultimate goal of social sustainability. A citizen could be an employee, customer, or both, and a member of the local community. Employee well-being includes mental, physical, financial, and social well-being, and the main parameters vary from easy commuting, work-life balance, worker-centric job allocation, and personalization of workplace conditions (e.g., training, activity, equipment) as per worker ergonomic factors (e.g., physical characteristics, capabilities, competence, experience, and knowledge) to personal development initiatives and lifelong education for employees.

A high degree of personalization delivers a superior customer experience and leads to customer satisfaction with the product and service provided: customer well-being. Finally, the collaboration between the USF and local communities is beneficial for manufacturers to improve innovation in products and processes. There are also advantages for local communities, such as funds for research, vocational training, and scholarships.

The economic dimension of sustainability consists of value creation and new business model development. Productivity, product variety, PSS, and FaaS are key parameters.

The ability to anticipate potential (internal and external) adversities and adapt to changing circumstances is the resilience of the USF. Status awareness, the ability to predict the future by analyzing past trends, the existence of metrics for comparison, flexibility, and adaptability are critical aspects of USF resilience.

The most important characteristics of an SF are connectivity, visibility, flexibility, and autonomy. For these features to be realized, several technologies are necessary, which will be reviewed in the following section. The main pillars of the USF and the major dimensions for each pillar are presented in Figure 3.

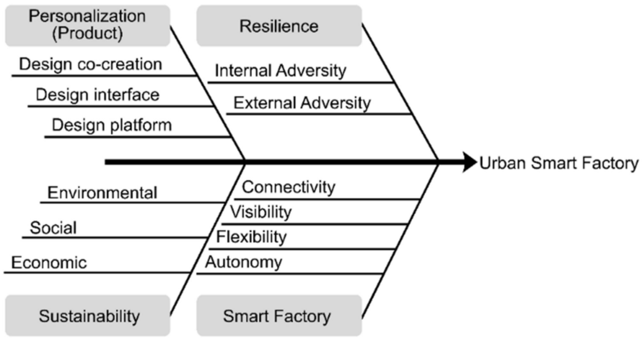

Figure 3. Pillars of USF.

4.2. USF Structure

An SF consists of four tangible layers: physical resources, network (data), cloud (and intelligence), and a control layer. The industrial network layer supports intercommunication between physical objects and communication between the physical resources and cloud layers. Information evaluation, knowledge management, and ontology modelling (which can provide self-organization, -learning, and -adaption skills) are included in the cloud and intelligent layers. Data analysis could support systematic groundwork for decision-making. Data mining can support design optimization and ensure active maintenance. Finally, the control (terminal) layer connects individuals to SF for remote monitoring of operation and maintenance, as well as to visualize the results of cloud computing. Through the intelligent terminal, customers can check orders in real-time [56,59,88].

USF consists of the same four layers, with at least three additional interfaces: customer design, product lifecycle management, and collaboration.

- The customer–design interface provides customers with easy and comprehensive virtual design tools and attractive visualization.
- The product lifecycle management interface gathers product data at the usage stage for product performance analysis and future design improvement purposes and facilitates recycling and reusing activities.
- Collaboration with local communities, such as excess energy sharing, education, and open innovation, can be managed by a collaboration interface.

4.3. USF Core Technologies and Key Manufacturing Systems

IoT, Sensors, CPS, DTs, Big Data and Industrial AI, 3D printing, and MR are core technologies of USF. The key USF technologies are shown in Figure 4.

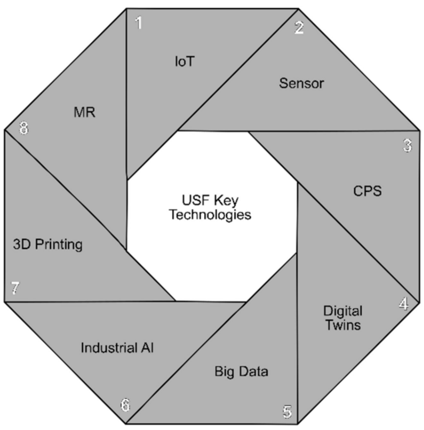

Figure 4. USF key technologies.

As real-time connectivity is vital to the USF, IoT supports interconnections in all activities from design (co-creation), supply chain management, manufacturing management, and maintenance to product monitoring and customer service.

Sensors are necessary for visibility at the manufacturing stage, where data from materials, products, machines, workers, and the environment should be collected for monitoring, optimization, safety, and autonomous control.

The 5C architecture has been proposed for the implementation of CPS, while self-aware, self-predict, self-compare, self-configure, self-maintain, and self-organization, the major attributes of Industry 4.0 smart factory, are achievable by realizing CPS [89]. CPS is one of the most important components of the USF that supports effective personalization, sustainability, and resilience. CPS is a platform that covers all five major parameters of personalization. It guarantees a high degree of personalization while ensuring engineering feasibility, product quality, required delivery time, affordable price, and product and process sustainability.

While CPS focuses on sensors and actuators, DTs focus on models and data [90,91]. By creating virtual models for physical entities, DT goals are simulated entity behavior, monitoring the status, identifying internal and external difficulties, perceiving unusual patterns, mirroring system performance, and forecasting upcoming trends [92]. DTs should be used in the USF's entire value chain, from design, supply chain management, scheduling, production and inspection management, worker health and performance management, and maintenance to product monitoring at the use stage.

Conversion of high-volume, fast-generating, and various types of data to meaningful information and knowledge for co-creation, collaboration, and proactive decision-making are only possible by utilizing big data and industrial AI. A worry-free production system (zero accidents, pollution, waste, defects, and downtime) is achievable through an industrial intelligence system [53].

3D printing (also known as additive manufacturing, layer manufacturing, or rapid prototyping) is required in the USF to quickly produce personalized modules or parts needed in the manufacturing process (e.g., jigs and gripers).

An MR environment is defined as one in which real and virtual world objects are displayed simultaneously on a single screen [92]. Augmented reality (AR) is regarded as an effective human-machine collaboration interface, with multiple applications in manufacturing that vary from operations, maintenance, assembly/disassembly, planning, monitoring, and quality control to process simulation, facility layout, and technical training [93].

At the USF, as a human-centric factory, AR has significant benefits for employees in terms of training, collaboration with machines, task assistance, and maintenance. The ability to interact with virtual information displayed in real-time makes MR an attractive technology for the design stage for both customers and employees.

Distributed, decentralized, and modular manufacturing systems enable personalization while facilitating sustainability goals and resilience. These systems also contribute to solving problems associated with urban production, such as spatial limits and logistics.

Since personalization is an important aspect of the USF, a modular manufacturing system is essential for the real-time capability to respond to customer design at the manufacturing level. Modularity also improves flexibility and resilience in terms of internal system fault settlement in real-time. Modular, distributed, and decentralized manufacturing systems are appropriate solutions for one of the most critical urban production issues: spatial limits. Decentralized manufacturing supports USF (through decentralized decision-making) to improve flexibility and cost-effective personalized manufacturing.

As explained in the previous section, modular product design is a critical strategy for personalization. In distributed manufacturing, mass-produced modules could be produced somewhere different from personalized modules, and final steps, for example, assembly, can be performed closest to the customer. Intelligent decision-making about production and supply chain routes critically affects the cost and lead time.

Logistics and traffic are other critical issues considered in the USF concept. Underground cargo, electric vehicles, and drone delivery systems are alternatives for the urban transportation of goods.

The characteristics of the USF, SF technologies and relevant purposes are summarized in Table 4.

Table 4. Characteristics, smart factory technologies, and relevant purposes.

USF Characteristics	Type	Smart Factory Technologies	USF Characteristics
Human-centric	Customer Employee	IoT, CPS and DT, Big data, AI, 3D Printing, MR, Wearables, on-demand manufacturing, modular, decentralized, and distributed manufacturing	Customer satisfaction Workplace well-being Higher employer attractiveness
Sustainability	Environmental Social Economy	IoT, Sensor, CPS and DT, Big Data, AI IoT, Sensor, CPS and DT, Big Data, AI, MR, 3D Printing IoT, Sensor, CPS and DT, Big Data, AI, MR, 3D Printing	Minimize emission and pollutants, Energy/Resource efficiency, Design for circular economy Education, Open innovation, Energy/Resource share, Product and Service Innovation Value creation, New business model development
Resilience	Internal adversity External adversity	IoT, Sensor, CPS and DT, Big Data, AI, MR CPS and DT, Big Data, AI, 3D Printing	Worry-free Production Flexibility, Dynamic scheduling

4.4. Benefits

We have briefly introduced several cases that demonstrate the application of SF technologies for the realization of personalization, sustainability, and resilience in urban production. The relation of each case study with the major points of USF and the expected benefits are summarized in Table 5.

Table 5. Case studies for USF with their relevance to USF's concept, structure, core technologies and benefits.

Case	Concept (Pillar)	Core Technologies	Benefits
Knit For You	Personalization	3D scanning and real-time simulation	Affordable personalized product, shortened design and production time, and supply chain
CTC	Personalization Sustainability (environmental, economic)	IoT, cloud, modular product design, real-time update of production data monitoring	Customer satisfaction, shorter supply chain, reduced waste, image and appearance shared have impressed a high number of visitors of the shopping mall
DigiPlex	Sustainability (Environmental, economic)	-	Reuse of waste heat of data center for heating residents

Table 5. *Cont.*

Case	Concept (Pillar)	Core Technologies	Benefits
Alpha Biofuel	Sustainability (Environmental, economic)	-	Material and resource efficiency
Wittenstein	Sustainability (Environmental, social, economic)	Smart sensors, IoT, CPS	Improving workplace well-being, low noise and emission, sharing of residual heat with surrounding urban areas
FaaS/CMSF	Personalization Sustainability Resilience	DT and CPS, 3D printing	Real-time monitoring of the present, tracking information from the past, and operational decision-making support for the future, reducing the cost and production inefficiencies
Nobilia	Personalization Sustainability	Smart sensor, IoT, CPS	Optimizing the degree of personalization, optimizing customer experiences, shortened manufacturing time, reducing waste materials and energy, practical production of products in a wide variety and high volume
VW T-Factory	Personalization Sustainability	-	Optimizing customer experiences
E-Forest HMGICS	Personalization Sustainability Resilience	Smart sensor, IoT, CPS, Collaborative robots	Optimizing customer satisfaction, improving workplace well-being, share infrastructure for global research and development experts and collaboration with local communities

5. Conclusions

This study proposes a conceptual definition of the USF, which aims to obtain the greatest benefits of the potential of urban production and deal with associated problems through SF technologies. To the best of the authors' knowledge, no such definition exists.

Through a literature review, the diverse potential of urban production, such as customer involvement and co-creation for a higher degree of personalization, connected-continued innovation, shortened lead time and supply chain, reduction of the value chain and production time and cost, lessened transportation emissions, availability of workforce, especially highly qualified experts, and higher employer attractiveness are analyzed. Along with the potential, major challenges of urban production, such as spatial issues, regulations, emissions and pollutants, smells, noise and vibration, and logistics and traffic, have been noticed.

To maximize the abovementioned potentials and deal with the challenges, we proposed USF as a human-centric factory with four pillars: personalization, sustainability, resilience, and SF.

Individualization is one of the most recently cited megatrends. Product/service personalization, directly connected with customer experience and satisfaction, is an essential goal in the manufacturing sector. However, customer involvement in the design phase affects all product lifecycle stages. SF technologies such as IoT, CPS and DT, big data, industrial artificial intelligence, 3D printing, and MR support transparency for manufacturers and guarantee desired product quality, required delivery time, and affordable price.

Sustainability is a multidimensional concept that covers megatrends under three categories: environmental (climate change, emissions, and energy and resource scarcity), social (demographic changes, human well-being), and economic (value creation and new business model development). SF technologies improve energy management and reduction of emissions, optimize resource efficiency, and support workplace well-being. They also create more opportunities for innovation and improvement in services and products.

Resilience is the ability to anticipate potential (internal and external) adversities and adapt to changing circumstances. In terms of internal adversities, self-resilience is mainly achieved through CPS, big data, and industrial AI.

SF characteristics such as connectivity, visibility, flexibility, and autonomy support manufacturers to maximize the degree of personalization while striving for excellence in sustainable and resilient manufacturing. SF technologies directly influence all the other three pillars of USF, as explained above.

The contributions of this study include the proposed conceptual definition of an innovative manufacturing paradigm that aims at personalization, sustainability, and resilience by utilizing SF technologies. Likewise, the characteristics, pillars, structure, and core technologies of the USF are defined. A USF as a human-centric factory optimizes customer experience by maximizing the degree of personalization. Moreover, utilizing SF technologies, especially CPS and DT, improves workplace well-being and employer attractiveness. As a sustainable factory, the USF is concerned with environmental issues and attempts to enhance resource and energy efficiency while reducing waste and pollution. In addition, collaboration with local communities brings innovation to products and processes. In case of an abnormal event occurrence, USF, as a resilient factory, would be able to quickly return to its regular operation through AI and DT applications. The contribution of SF technologies to the achievement of primary USF goals is clearly described.

Furthermore, case studies with significant utilization of one or more pillars of the USF are specified. In terms of personalization, customer-designed knit and furniture, for sustainable manufacturing, energy and resource efficiency (reuse of waste heat, recycling of used cooking oil), servitization and new business models (educational/recreation events), energy sharing, reduction of noise and emissions, and for resilience, predicting the operation, production, and support decision-making are observed.

As we could not find a practical model that completely aligns with the definition of the USF, the limitation of this study is that the empirical evaluation of the proposed definition and expected benefits of USF is not possible. Although, we believe that there will be cases that fully demonstrate the proposed USF characteristics and expected benefits simultaneously. HMGICS that is planned to open in the second half of 2022 comprises all aspects and attributes of the proposed USF regarding personalization, sustainability, and resilience through the realization of smart manufacturing technologies.

Since this paper focuses on the concept, structure, core technologies, key manufacturing systems, and USF benefits, there are more areas to be studied in the future. First, it is necessary to evaluate the appropriateness of the targeted product and industry for the USF model. Second, it is important to investigate the interdependency of USF major goals and identify key performance indices with a higher impact. In addition, a maturity model for the step-by-step continuous realization of USF is required. Finally, and most importantly, developing a customizable assessment model to evaluate and determine the level of readiness of the conditions, attitude, resources, and technologies at all levels of USF to accomplish its stated goals is required.

Funding: This research was financially funded by the Ministry of Trade, Industry and Energy (MOTIE) and Korea Institute for Advancement of Technology (KIAT) through the International Cooperative research and development program [P0009839, Cyber Physical Assembly and Logistics Systems in Global Supply Chains (C-PALS)] and Materials and parts technology-based innovation research and development program [N0002602, The Construction of a Virtual Engineering Platform for Fiber Composite Structures].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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