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# Increasing resilience of material supply by decentral urban factories and secondary raw materials

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Current production processes are frequently dependent on global supply chains for raw materials and prefabricated inputs. With rising political and global risks, these supply networks are threatened, which leads to a reduction of supply chain resilience. At the same time, urban areas are currently one of the main consumers of products and waste material generators. The raw material sourcing for this consumption commonly takes place in globally connected supply chains due to economy of scale effects. Therefore, cities are especially vulnerable to supply chain disruptions. A recent development which could reduce this vulnerability is the installation of urban factories among other urban production concepts, which can be symbiotically embedded into the urban metabolism to utilize the locally available (waste) materials. This, however, is hampered by the smaller production scale of decentralized urban production facilities, limited knowledge and challenges about the urban material flows and their characteristics. Against this background, we introduce a new factory type which is placed between the primary and secondary industrial sector: An urban secondary raw material factory which utilizes local waste material and other urban material flows for the extraction and refinement of secondary raw materials to supply production sites in its surrounding environment. To enable this small-to medium-scale factory type, the application of new production technologies plays a crucial role. Therefore, this paper proposes an approach for matching relevant potential waste streams to different technologies for waste-to-resource refinement. The applicability of the method for identification and evaluation of suitable technologies regarding their potential to be located in urban environments is demonstrated for plastic and metallic materials. Subsequently, key challenges and characteristics of the new factory type are summarized. With the introduction of this new factory type, the lack of scale effects in urban symbiotic networks is expected to be reduced. In conclusion, challenges such as the data-based management of symbiotic relationships among manufacturing companies are highlighted as still relevant in decentral value chains.

KEYWORDS

**resilience, urban manufacturing, urban factory, recycling, urban metabolism, resource efficiency**

# 1 Introduction

Global urban population is increasing. Currently, 57% of the global population lives in cities and urban regions. For the year 2050, the United Nations expect a rise to 66%. Given an expected global population increase, the absolute number of people living in urban areas will increase from 4.3 bn to 6.4 bn (United Nations, 2021). Urban areas account for a high share of value creation and are therefore important motors of global economy. While cities account for a large portion of consumption, they are mostly not involved in the primary and secondary sector (Pike, 2022), which is the result of limited space for primary activities and the historic change of the relationship between production and the urban environment. Thus, supply chain interruptions can have a large impact on urban living. For most urban regions, the dependency on global supply chains has had minor negative influence on the economic development in the past due to a relatively stable environment. However, different economic, political, and pandemic shocks in last decade have shown the vulnerability of global supply chains.

According to Freeman et al. (2017), cities are especially vulnerable to extreme weather conditions, industrial accidents and environmental pollution, transport accidents, infrastructure failures, human and animal health crisis, industrial action, loss of access to finance and ability to import materials. With a disturbance in supply chains, the ability to import materials will decrease and urban life is threatened. Recent examples for supply chain disturbances can be seen in the disruption of supply chains due to the COVID-19 pandemic (Ivanov and Das, 2020) or the grounding of a container ship in the Suez (Lee and Wong, 2021), which had short- and long-term effects on goods supply. Against this background, cities as well as manufacturing industry strive towards increased resilience. Fiksel (2006) defines resilience as the capacity to survive, adapt and grow in the face of turbulent change. According to a literature review conducted by Hohenstein et al. (2015), supply chain resilience can be divided in the four phases readiness, response, recovery, growth. In the context of cities, a sufficient level of supply chain resilience (SCRES) is a key requirement to provide and sustain stability and is therefore desirable and strategies to achieve SCRES have to be developed.

A possible contribution to strengthen SCRES can be a revitalization of decentral urban manufacturing (Singh et al., 2017; Herrmann et al., 2020). Key characteristics of these urban production systems are the utilization of their unique urban surrounding and the consideration of the specific local challenges and opportunities. A high potential also lies in embedding a production site in local material flows and the urban metabolism (Kirchherr et al., 2017; Tsui et al., 2021b). In this regard, one scenario is the utilization of urban mines, which are defined as the material in compounds and elements from anthropogenic stock (Lederer et al., 2014). Another source for materials could lie in the involvement of industrial (Jacobsen et al., 2006) or urban symbiotic (Chen et al., 2012) networks, which are understood as the exchange of waste flows between industrial or a broader variety of urban actors as inputs for production processes. These concepts of locally embedded production systems are often associated with environmental benefits (Diez-Ladera, 2016) and can contribute to SCRES. The capability for businesses to cope with vulnerabilities comes at an economical price and therefore has to be adapted to the actual risks to operate businesses in a profitable state (Pettit et al., 2010). For the case of local manufacturing and material utilization, a decrease in production scale can be expected and production systems have to adapt to varying input flows–especially when a direct waste material transformation is intended. To achieve economic feasibility, Chen et al. (2012) state that a certain material mass threshold has to be exceeded for a successful implementation of urban symbiotic systems.

Based on these challenges for the supply of urban production, a concept with an additional actor between urban material sources and production is introduced, the Urban Secondary Raw Material Factory (USeRMaFa). The development of strategies for the realization of SCRES in cities by embedding of USeRMaFas into urban environments is highlighted from a larger to a smaller scale in four chapters: The first chapter introduces different scenarios for the relationship between city and production, the second chapter discusses the principle of the USeRMaFa and details the embedding to the urban metabolism. The third chapter discusses requirements for process chains and technologies and the fourth chapter gives examples for possible technological utilization. The concept is tailored towards plastic and metallic materials, which are currently circulated globally (Chen et al., 2012). Especially regions with limited resource availability, such as Western Europe, will therefore suffer from supply chain disruptions. The demand for local concepts is also increasing due to limited trade opportunities and the associated higher export costs. Germany, for example, drastically reduced its exports after an import ban on plastics was declared in China (Statistisches Bundesamt, 2022 7th). The use of collected waste in cities to close material loops is one way to address these challenges, and the proportion of material used in this way is a good indicator of their vulnerability. Currently, this opportunity is hardly used, as shown by the case of Brussels, representative of European cities, where the share of waste utilized in this manner is less than 1% (Zeller et al., 2019). The strategies developed aim to increase resilience and therefore provide approaches on how to increase this ratio. Since material flows and inner-city material cycles are focused on, cities and the integration of production within them are presented in the following with material flow-centred models.

## 2 Urban production as resilience enabler

The integration of production into urban areas is visualized in Figures 1–3 for three scenarios. The city is described as a system with boundaries which are indicated by the dotted line. Across these boundaries, flows of materials, energy, personnel and information can be identified. Reduced in the context of supply chains to material flows and exemplified with the case of a production system, the system can be modelled with input and output flows. The single input flows are realized by supply chains with system-external factors which have different grades of SCRES. The number and volume of resulting material flows across the system boundary is represented in the number and size of the respective arrows. The system is modelled in a state with a constant mass balance, in which the material input and output flows have the same volume and there is neither an increase nor a decrease in the total amount of material within the system in the considered period. These material flows across the system boundaries can be described as product flows into the city and waste flows out of the city. Within the system, these flows are transformed by different actors. Not only can the system boundaries of this model be scaled, which enables the inclusion of various analysis levels, but the input and output flows can also represent the sum of all material flows or individual material groups or materials in the spectrum. Thus, the model can be used for different cases of spatial considerations as well as for total mass flow, material or product-related analyses. Figure 1 shows the scenario “productionless city”. In this scenario, the transformers are the product users. Hence, the system is absolutely dependent on product input from external sources. Additionally, an equivalent waste flow is generated, which has to be recycled or stored outside the system. It thus shows a high dependence on actors and

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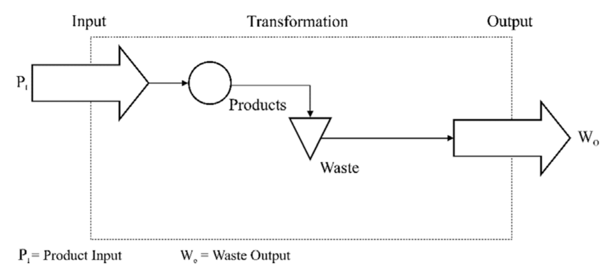


FIGURE 1
Productionless city.

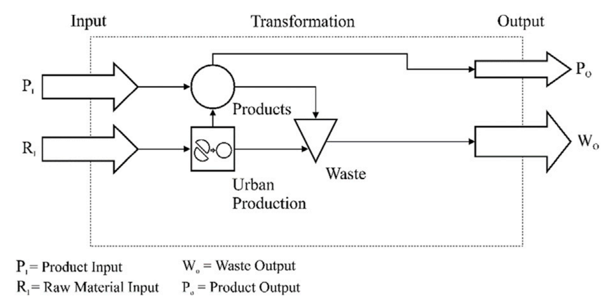


FIGURE 2
Productive city.

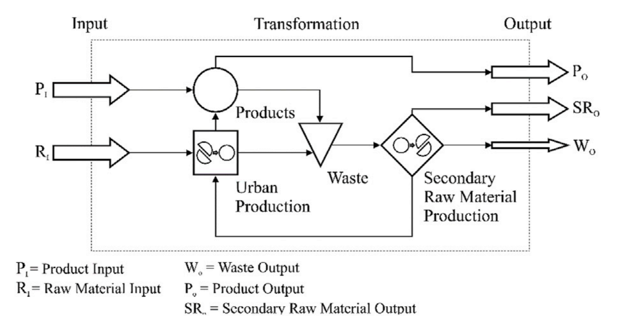


FIGURE 3
Symbiotic productive city.

conditions outside its own system. The city depicted in this scenario is therefore dependent on external supply of manufactured goods and no added value is generated by goods production.

Figure 2 shows the scenario "productive city". In this scenario, another transformation process can be observed. Simplified, raw material is transformed into products and by-products within the system boundaries. Therefore, a new input flow is created. Raw materials that are not directly available in the city must be imported. On the other hand, after transformation through production, products are available which, if not used in the city and transformed into waste flows, cross the system boundary as product output flow. The flows within the system get more complex with the production producing waste as well. In this case, the source for the products needed in the system can be partly within the system itself. Adding another transformation process reduces the input flow and thus the dependence on external factors for finished products. On the other hand, a new flow of raw materials is added that crosses the system boundaries and represents a further dependency. Increasing the number of dependencies can reduce the risk associated with a single dependency. In addition to the waste flow, a product flow of the products manufactured in the system can also be introduced from the system. This also creates further dependencies, but there is also a diversification of external influencing factors, which can reduce risks.

Figure 3 describes the scenario "symbiotic productive city". The symbiotic productive city has the lowest cumulative mass of all system boundary crossing input flows, and due to the constraint of an equilibrated mass balance also output flows, symbolized by the lowest cumulated area of the system boundary crossing arrows (PI, RI, PO, SRO, and WO). This means that mass flows that would otherwise be realized as output will be transformed in a way that allows them to remain in the system. The city's internal production can specifically produce products that meet internal demand, which reduces product flows out of the city and also reduces product flows into the city while waste flows that leave the system can be reduced. This reduction can be achieved by transforming by-product and waste flows into new raw material. This increase of material efficiency results in a reduction of the raw material mass to be introduced into the system. The secondary raw material can as well be utilized for export which results in reduced costs compared to the export of waste materials. In this case, the number of possible output flows outnumbers the number of input flow categories. This shift towards minimal input demands but diversified output opportunities can also lead to an increase in system resilience as the output of more valuable and diverse material classifications can be increased. The overall effects of supply chain disturbances are reduced within this third stage of the model. The inward allocation of value-adding activities can affect the economic resilience of the system under consideration. This addition of another system internal transformation process diversifies external dependencies and at the same time reduces the dependence induced risks to a minimum. To enable the "symbiotic productive city" scenario, a facilitating additional actor can be integrated in different ways. The next chapter gives an overview of different possibilities of integration and introduces the production-related entities in symbiotic urban networks, leading to the introduction of the aforementioned complementary actor.

## 3 The urban secondary raw material factory—Symbiotic embedding into urban environments

Local producers can be categorized into different categories. Tsui et al. (2021a) differentiate between four categories of urban manufacturers: (i) personal fabricators are hobbyists, which make products for personal use, (ii) maker spaces are shared workshops for makers, (iii) mini-factories are small to medium sized factories with fewer than 20 employees and (iv) traditional urban industries are large-scale manufacturers, who have chosen to stay in the city or to purposefully utilize the opportunities of the urban system. Other categories, such as traditional craft manufacturers (carpenters, shoe makers, etc.) as well as "unintended"

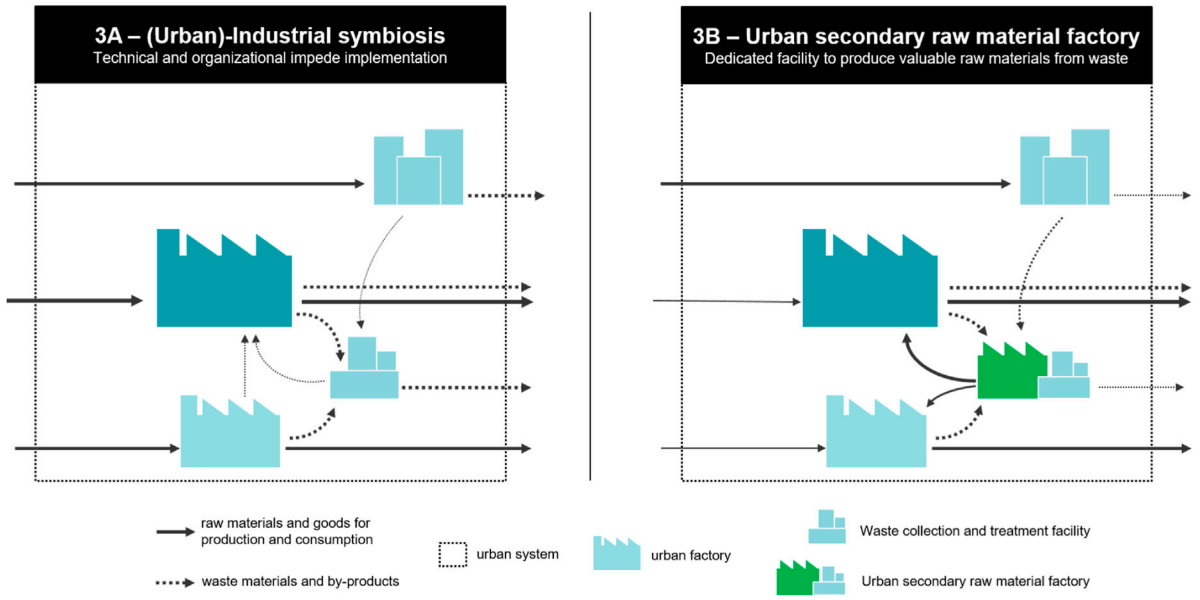


FIGURE 4
The urban secondary raw material factory and its integration in the urban metabolism.

urban manufacturers [for example because the urban area grew around them (Herrmann et al., 2020)] could also be an addition to the list of urban manufacturers. This heterogenic mass has different production scales and different demand for input materials. Therefore, urban production networks are challenged to adapt to these differences. To realize the adaptation, we introduce different scenarios for the integration of factories into urban environments in the following section.

Figure 4 shows different concepts for the material flow integration of urban factories into their surrounding environment according to the previously introduced scenario 3. Here, two sub-scenarios are envisioned. The images show a city-production system with different internal and external material flows. Scenario 3A shows a utilization in form of (urban-)industrial symbiosis, as introduced by Chertow (2004) ("industrial symbiosis consists of place-based exchanges among different entities that yield a collective benefit greater than the sum of individual benefits that could be achieved by acting alone.") and extended to urban actors like households by Chen et al. (2012). In this concept, the materials are circulated in loops inside of the city system. The outputs from one actor are seen as inputs for other actors. Per definition, the material receiver aims to transform waste to end-products. The input and outputs of the city are therefore reduced and fewer materials have to be im- or exported. The direct material input leads to several challenges regarding the material continuity as well as the possibilities for quality control. This leads to reduced possibilities for contribution of smaller producers–especially as material receivers and stands against the definition of *Chertow*, which envisions a collective benefit.

The introduction of an aforementioned additional actor–the USeRMaFa–can provide such a collective benefit and is illustrated with Scenario 3B. This factory type is seen as an additional actor that produces semi-finished parts. The resulting parts can be utilized in flexible, distributed production processes by urban producers, thus reducing the burden for urban producers to operate in a higher scale, because the transformation is performed on the largest possible urban scale and the output materials can be used from the different actors. Additionally, the USeRMaFa is able to transform material from the so-called urban mine in form of landfills or currently circulating products. Therefore, it helps to reduce already existing pollution. The integration of this additional step offers the potential to create additional added value, reduced necessary external material input and overall reduced transport routes. The city is less endangered regarding supply chain disruptions, because a source redundancy and a structure for reutilization exist. With knowledge about transformation processes, this approach also becomes economically more viable, as a higher yield can be expected with lower external supply and remaining demand.

To unlock the described potential of the introduced factory type, several challenges arise regarding the usage of materials, the integration into urban environments as well as the process chains and production systems. These are discussed in the following sections.

## 4 Technology and process chains for USeRaMaFa

The introduction of USeRMaFa into urban space as a system element can support urban manufacturing, which takes place in so-called urban factories. The concept of purposeful urban factories and sustainable urban manufacturing has gained increasing research interest in recent years. Current concepts and developments are focused on tapping the positive potentials while coping with the specific challenges and requirements of urban factories.

### 4.1 Requirements for urban factory production systems

Urban space can be defined as a densely populated, multi-functional settlement structure, which as a location enables specific

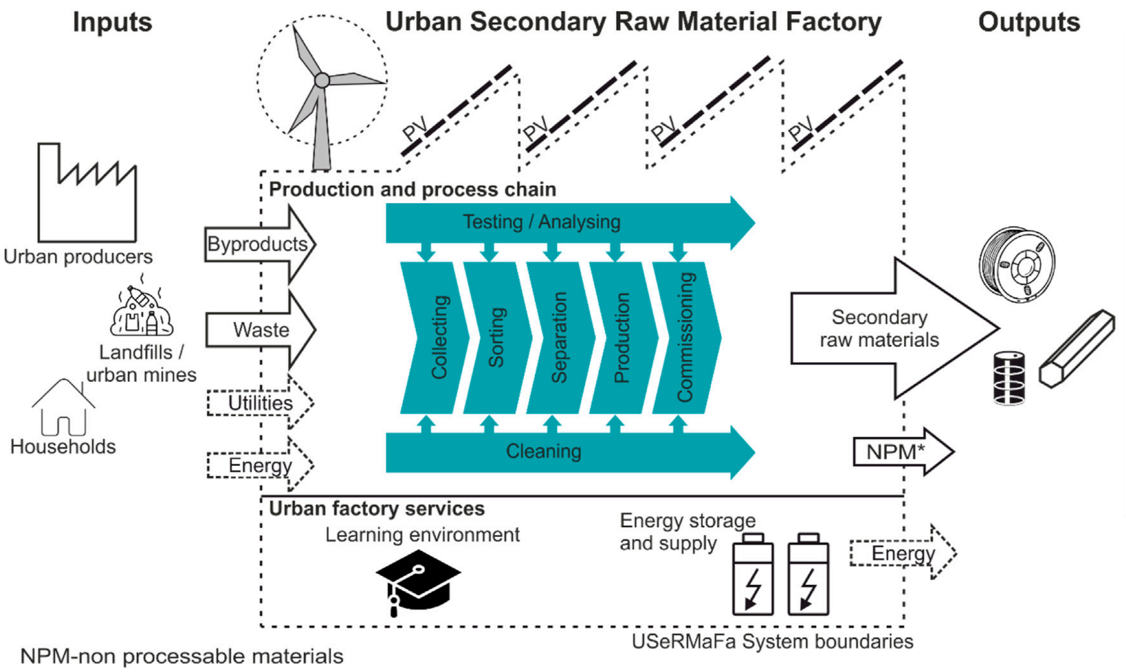


FIGURE 5
USeRMaFa characteristics and internal material flows.

potentials for urban factories but is at the same time associated with challenges (Juraschek, 2022). In less densely populated areas, beneficial characteristics for a production site include in most cases low land costs, availability of expansion space and low interference potential from other stakeholders. In a city, vicinity to customers as well as potential employees, urban infrastructure and the opportunity of implementing localized product-service-systems are among the potential benefits. An urban factory is utilizing the locally available resources, as for instance space, energy and knowledge (Juraschek et al., 2018b), and stands in competition with other stakeholders. Thus, factories in urban environments frequently face conflicts delaying or preventing expansion processes and growth or threaten the survival. As a consequence, any technology employed at an urban factory is required to comply with the constraints that are imposed by its location and surroundings. These constraints include, for instance, stricter limits for noise or odor emissions, limited expansion space or higher demands on architectural quality. Going beyond the strategy of lowering negative impacts of a factory, the concept of a holistic Positive Impact Factory was proposed by Herrmann et al. (2014) and Herrmann et al. (2015). By actively integrating and utilizing the specific potentials of urban space, an urban factory can also provide services or urban functions, as for instance education, value creation or product supply, to its surroundings.

Figure 5 shows a zoom-in on the USeRMaFa in its immediate urban environment and highlights the core elements of the factory. Positive contributions to the surrounding system as introduced by Herrmann et al. are indicated by the installed energy generators (PV and wind turbines), the energy storage as well as the utilization of a learning environment.

The left-hand side shows possible input sources. These are described in Section 2 and include urban producers, landfills/urban mine and households. The generated input flows are byproducts from production processes, waste materials, as well as utilities. Here, a challenge is the mix of materials, which requires a highly flexible manufacturing environment to adapt to the different materials and qualities. Local factors, such as the legislative environment also play a role and have a high influence: With stricter regulations for waste separation and collection, lower effort has to be taken in the earlier production stages of the USeRMaFa. Additional utilities include for example virgin materials to mix, auxiliaries, and operating supplies such as coolants and lubricants. These additional utilities cannot always be derived from waste materials and should therefore be reduced to the necessary minimum.

In the image center, the production system of the USeRMaFa is depicted. The process chain includes the phases collecting, sorting, separation, production and commissioning, as well as overarching cleaning and testing. In the collecting and sorting phase, the different inputs are stored to overcome the threshold for an economically sound material amount for production. To account for inconsistent input streams, bypass storage capacities can be necessary, which can be a cost factor. The necessity of bypass storages can be reduced in a connected smart city network. With a knowledge of industrial byproducts, planning processes for urban material transformations can be improved (Raabe et al., 2017). Because of possible contaminations, cleaning has to be throughout the transformation processes. In this regard, the necessary amount is dependable on the material type itself, the transforming processes as well as the contamination. To compensate for different input material qualities and properties, the process chain has to be supervised by quality assessment throughout the whole process chain. In this regard, higher efforts than in conventional process chains can be expected.

The right-hand side indicates the output material in form of secondary raw materials. The shape of these materials highly depends on the recycled materials and on the used transformation processes. For steel or aluminum-based materials, the output could consist of bars, semi-finished profile bars or sheet metals. Higher valued metals such as copper, silver, or gold could be transformed to ingots. In case of polymer materials, the output materials could include filaments for additive manufacturing processes, pellets for molding and extrusion processes, or olefins and aromates. The shape of these output materials is highly dependent on the production processes. The following sub chapter introduces an excerpt of possible urban compatible processes for different material categories.

### 4.2 Material processing in USeRMaFas

Material processing is a crucial element for the installation of USeRMaFas, as the utilized technologies have to be able for small scale and discontinuous operation and an adaptation to different input materials and qualities must be possible–near zero waste should be targeted. Additionally, the processes must comply to the introduced low interference with other urban actors while also providing high quality materials. This means, that many traditional process chains for secondary raw material production do not apply. Recent technological developments show potential for utilization in USeRMaFas. As an example, for plastic materials, several routes can be possible. In general, a differentiation between thermoplastic polymers, thermosetting polymers and elastomers. While thermoplastics offer the possibility to be remold or formed, the options for the latter are limited. To access repurpose thermoplastics to secondary raw materials, literature offers several options. The simplest solution would consist of a direct remolding to later useable structures like pellets or filaments, but degradation over the extended lifespan can occur and reduce material quality. The necessary machinery can be created in smaller scale and with relatively low effort, as shown with the construction of a process chain for the recycling of PET-wastes to Fused-Deposition-Molding (FDM) filaments in learning factories (Juraschek et al., 2020). Similar approaches are also realized by the company *Recyclingfabrik*, which collects PLA wastes from 3D-printing and recycles them to new filaments (Recyclingfabrik, 2022). To avoid degradation and reduce the influence of contamination, plastic materials can be treated by chemolysis. The RevolPET technology is able to recover the monomer materials [ethylene glycol (EG) and the corresponding salt of terephthalic acid (TA)] in an extrusion process from PET (Biermann et al., 2021). For other polymers and their combinations, pyrolysis offers one possibility to reduce the polymers to olefins and aromates which can be reutilized for the generation of new plastic materials by pyrolysis (Costa et al., 2021). A similar approach has been adapted for industrial use. The WASTX Plastic technology is a production system, that can be installed in shipping containers and contains the auxiliary processes (cleaning and separating) (Bio Fabrik, 2022). Therefore, these production systems offer the possibility for an installation in urban environments. While pyrolysis offers the possibility for high secondary material quality, it is also connected to high energy consumption. Especially material mixes lead to an increase of necessary energy to break the structures (Erkisi-Arici et al., 2021). The necessary investment and effort is therefore dependent on the quality of the input materials and the quality requirements for the products–which is highly dependent on local legislation.

Metals can be recovered by many different approaches and high recycling rates are already possible. Traditional methods like blast furnacing have high spatial and energetic requirements and are therefore usually placed outside cities. With mixed input materials and discontinuous supply, more flexible strategies should be utilized. Pyro-, hydro-, solvo- and biometallurgical processes can recover a high amount of low-grade materials, but are also connected to higher energy or process efforts (Spooren et al., 2020)–and are not necessarily compatible to urban environments due to hazardous materials. Therefore, the USeRMaFa should utilize smaller and low effort strategies which avoid globally applied remelting. For example, the Temconex® process is a continuous extrusion process which can transform chips and powders to high density profiles (Saefkow et al., 2017). Aluminum based sheet scrap materials can be recycled through friction consolidation (Baffari et al., 2019). Depending on the previous material strain, a cold reforming of sheet metals is possible (Takano et al., 2008), which can reduce the necessary energy input. Paraskevas et al. (2015) introduce a method for spark plasma sintering of aluminum sheet metal scrap. Utilizing the flexible, small scale sintering process, it was possible to generate full-dense parts without full remelting.

The shown technologies show an excerpt of possible processes for USeRMaFas. The approaches offer higher flexibility and show promising results for an efficient utilization in small/meso-scale operation. Depending on the recycled materials, the decision whether to apply energy intensive methods has to be made under consideration of economic, such as processing and logistic costs, discontinuity risk, differences between generation and destination, research for new uses, support of new products, extended life of deposits and landfills, and compliance with legislation in operation strategy (Sellitto et al., 2021), as well as ecologic factors. The economic feasibility can however increase with an increase in supply chain disruptions and higher material scarcity.

## 5 Discussion: Potential contribution to resilience factors of an urban factory

As a general definition, resilience describes the capacity or ability of a system to adapt or transform in response to significant internal or external disturbances, shocks and general change processes (Carpenter et al., 2012; Biedermann et al., 2018b). A resilient system is more likely when experiencing such disturbances to preserve its functions and in response to reorganize and restructure itself. This process can be summarized in four properties of readiness, response, recovery and growth (Hohenstein et al., 2015). Resilience can be formed against expected events, which is referred to as specific resilience, or regarding unexpected and unforeseeable disturbance, which can be defined as general resilience (Carpenter et al., 2012).

In either case, resilience as a system property can be seen as the opposite to vulnerability. Due to the numerous possibilities of potential disturbances that might occur and complex interconnections in socio-technical systems, it can be complicated to define quantifiable measures for resilience. One approach to analyze a system's resilience is to investigate the characteristics of contributing or limiting factors. These resilience factors can include but are not limited to redundancy, diversity, modularity, reserves, feedbacks, nestedness, trust, flexibility, transparency, agility, governance, reactivity, adaptability, sharing, robustness, responsiveness, distribution, experimentation, risk reduction, openness, and

**TABLE 1 Influence of USeRMaFas on resilience factors.**

| Resilience factor | Potential contributions | Potential challenges | References |
|---|---|---|---|
| Redundancy | Additional local raw material sources by tapping resources from urban waste streams | Potentially higher cost for production of secondary materials due to labor cost and urban land value | Juraschek et al. (2019) |
| Diversity | Provides alternative options for specific material demands; local response diversity enables several options for action | Might increase system complexity by introducing diverse reactions and behaviors for individual USeRMaFa | Juraschek et al. (2019) |
| Modularity | Can prevent or dampen the spread of disturbances and shocks; allows local upgradability | Modularity and sub-division of system elements can increase costs, raise complexity and hinder transparency; decentralization raises dependency on local waste material flows | Hara et al. (2011) |
| Reserves | Supports the building of localized capacities to react, adapt, compensate and substitute failures in the supply chain | Can incur higher material production costs and might bind financial capital | Biedermann, (2018a) |
| Feedbacks | Short feedback loops allow the quick adaption to changing requirements or demand | Constant and intense local feedback can lead to required product and process innovation | Buecher et al. (2018) |
| Nestedness | Integration into urban system and local value creation networks can offer support to cope with disturbances | High density of urban areas and numerous different stakeholders might limit available actions and space for growth | Burggräf et al. (2019) |
| Trust | Local embedment and visibility can foster trust, which enables actions to be implemented in uncertain circumstances | Higher visibility can lead to increased exposure to different stakeholders | Dincer and Uslaner, (2010) |
| Flexibility | Allows adaption to changing requirements or demands by distributing production facilities | Providing flexibility can increase cost or lower overall efficiency | El Maraghy and Wiendahl, (2016) |
| Transparency | Increases the visibility of action-effect-relationships and thus provides more targeted options for intervention | High effort for acquiring, processing and provide information for transparency | Rappaport, (2019) |
| Agility | Smaller and decentralized production units can ease adaption to changing input parameters or customer requirements | Requires excess capacities or reserves to be activated, might prevent efficiency gains from experience | El Maraghy and Wiendahl, (2016) |
| Governance | Stable local governance can support implementation of actions and provides reliability | Higher effort necessary to maintain a capable governance structure; specific risks might arise form unstable local governance | Kinkel, (2009) |
| Reactivity | Short distances can decrease communication delays and increase reaction speed on occurring disturbances and shocks | Requires excess capacities or reserves to be activated, might prevent efficiency gains from experience | Biedermann, (2018a) |
| Adaptability | Allows adaptation to locally available material sources | Conflicting goals with highly efficient and uniform industrial mass-production paradigm | Biedermann, (2018a) |
| Sharing | With sharing of physical goods, risks or costs can be reduced. Sharing of immaterial goods such as knowledge can extend available capabilities | Sharing can also increase risks due to the exposure to other stakeholders and due to conflicting goals in material processing | Rappaport, (2017) |
| Robustness | Localized production systems can be adapted to the specific robustness requirements of local conditions | Smaller system size might hinder investing in robust process and facility design | Stricker and Lanza, (2014) |
| Responsiveness | Local embeddedment can increase openness to requests from local factories | Exposure to various influences in the urban system can lead to a high number and non-beneficial reactions and responses | Juraschek et al. (2018b) |
| Distribution | Distribution and decentralization of raw material refinement can divide and deconcentrate risks; transport effort can be reduced | Smaller and distributed production units contradict economy of scale and might lead to higher costs and efficiency loss | Mourtzis and Doukas, (2012) |
| Experimentation | Urban innovation potential and diversity can enable experimentation and development | Distribution and smaller system scale might hinder transferability and formalization | Gutzmer, (2016) |
| Risk Reduction | Decreases vulnerability associated with spatial distances and long supply chains | Raised exposure to risks specific to the urban location | Biedermann, (2018a) |

monitoring (Carpenter et al., 2012; Hohenstein et al., 2015; Biedermann et al., 2018b).

Introducing modularity by dividing a large system into smaller sub-systems, separating system elements through boundaries and defining and implementing interfaces, for instance, can prevent the spread of shocks and disturbances and thus raise the ability to remain functional, adapt and transform. Furthermore, modularity as a factor fosters interchangeability and upgradability of system elements. At the same time, splitting up system elements can increase efforts for exchange across the sub-system boundaries and–in the case of a production system–decrease overall efficiency. In Table 1 the potential contributions to the resilience factors of an urban factory by locally introducing a USeRMaFa into the city as well as potential challenges are summarized.

Establishing USerMaFas to locally utilize available material flows and transform these into useable raw materials as input for production systems can strengthen the resilience of urban factories particularly with the decentralization and distribution of potential raw material sources. This offers redundancy and diversity, which can support avoiding disturbances in long-distance and single source supply chains. Local nestedness of a USerMaFa and short distances to waste material flows as well as urban factories as customers provide advantages due to short reaction times, adaptability to local circumstances and transparency. These main potentials are at the same time imposing challenges regarding the resilience factors, for instance with dependencies on the quality and volume of local waste material flows, exposure to local risk factors and the smaller scale of the production system, which might lead to economic challenges.

# 6 Final remarks and outlook

This paper introduces the concept of an urban material transformation factory, which utilizes urban (waste) material flows for the creation of secondary raw materials. These can be utilized with the intention to support supply chain resilience and to create benefits for local value creation by urban manufacturing. To introduce possible effects of local material circulation and especially secondary raw materials, different urban material flow scenarios are discussed. Here, the introduction of industrial and urban symbiosis was introduced as contributor to SRES. Based on research on general urban factories and their integration into their urban surroundings, general characteristics for USeRMaFas were derived and selected production processes were introduced. With the potential of material transformation in close proximity to the material use, there also exist risks which are discussed in relation to general supply chain resilience factors.

Future research should address the multiple influences of the concept on the complex construct "city". In this regard, the ecologic implications of local material transformation should be addressed, as the lack of scale effects can increase the necessary energy input but can also reduce transport and resource extraction related emissions. On an economic level, as stated by Pettit et al. (2010), the capabilities which are necessary to overcome the disturbances in supply chains for WEEE-materials come with an economic price, which is on the one hand connected to the loss of scale effects when performed in smaller scale as well as on the other hand with the loss of possibilities to produce in low-wage regions. To improve efficiency of urban symbiotic supply chains, the management of symbiotic relationships between the involved actors should be further analyzed. This could be performed by modeling approaches utilizing data obtained from producers and their urban environment. In this regard, quantitative approaches, as introduced for industrial symbiosis networks (Demartini et al., 2022) could be further developed. In regard to current disturbances to supply chains, the increase of capabilities seems to be a potent solution–especially since there is currently a significant amount of materials stored in cities. In regard to an increasing resource scarcity and geopolitical disturbances, a shift towards local supply chains is therefore a promising approach.

On a social and human centered level, for (re-)location of production in the urban area, acceptance of the local population for the establishment this production type plays an important role. This can be examined from different perspectives and acceptance in the surrounding population could be considered with acceptance theory models (Davis, 1989; Venkatesh and Xu, 2012). Resilience increases of the USeRMaFas could in this case lead to an enhancement of the performance expectation. General behavioral models, in which social norms are relevant for the intention to act, (Ajzen, 1985; Graf, 2007), can be used to investigate the acceptance of the company management towards the settlement in an urban area. From the factors that influence the respective acceptance, it is possible to deduce what influence the production system can have on the establishment or perpetuation of urban production. In addition to the behavioral human-centered perspectives on urban production and its resilience, social aspects can also be the subject of further research. One aspect that can be examined in this context is the reduction of commuting (Novaco and Gonzalez, 2009).

A possible approach for multi-disciplinary research can be the development of demonstrators under involvement of the different actors. These approaches could be aiming to involve different perspectives; as urban manufacturing processes concern different actors. Possible contributions could include production engineering, urban planning, architecture, legal sciences, and sociologists to ensure a multi-dimensional perspective. Further research should also include public and economic actors such as governing bodies, technology suppliers, waste service suppliers and citizens.

# Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

# Author contributions

MK, JM, and GS conceived of the presented idea. MK and JM developed the factory concept and the embedding factors. MK lead the editorial process. HC encouraged MK, JM, and GS to further look into different embedding scenarios and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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# Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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