Micro-Factory in the City: Enabling Distributed Manufacturing and Last-Mile Product Customisation in a Model Factory Value Chain

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Abstract. As manufacturing companies strive to be more sustainable and resilient in their operations towards Industry 5.0, they face challenges in responding flexibly to dynamic demand, especially for urban customer-centric production where demand spikes, noise and emissions constraints, and last-mile logistics considerations limit their ability to make optimal decisions in coordination with value chain partners. A Learning Factory can play an important role not just to upskill industry to use technologies that can address these challenges, but also to serve as a testbed and even support co-innovation and small-scale production for companies to explore new value chain manufacturing paradigms. In this paper, we present such an example of the expansion of the SIMTech value chain to incorporate a new Micro-Factory located in another site closer to the city centre. The Micro-Factory leverages smart manufacturing platform capabilities to improve the demonstrative impact of the SIMTech ecosystem as a Learning Factory for training and outreach to industry, doing this by enabling multi-site manufacturing with a responsive cross-factory production system that leverages the high connectivity and availability of the SIMTech digital ecosystem for rapid deployment of high-mix low-volume last-mile product customisation capabilities. The Micro-Factory also supports accessible first-mile product collection for end-of-life products, a key step in enabling closed-loop manufacturing towards sustainable manufacturing in the SIMTech value chain.

Keywords: Micro-factory, product customisation, value chain.

1 Introduction

Learning factories play a crucial role in helping industries respond to new challenges in the post-pandemic era, especially in learning lessons from the value chain disruptions that were faced. By focusing on specific areas and aspects of industrial production,

learning factories can enable hands-on training and offer experiential learning opportunities for practical learning, innovation, and testing as companies try out new technologies, such as green manufacturing technologies, or new business models, experimenting with high-mix, low-volume production systems and rapid prototyping for co-innovation.

One of the challenges that companies often face, in the move towards a Industry 5.0 Human-Centric approach, is the increasing demand for faster response at enterprise and shopfloor level, especially in the context of being flexible to dynamic demand opportunities or addressing production issues with resilient, real-time decision-making. Especially in the context of high-mix, low-volume production where greater levels of personalization are required, one solution for industries is to move to a diverse and distributed paradigm of value chain manufacturing, where partners are able to make decentralised decisions autonomously yet synchronously.

However, when considering multi-site or multi-enterprise manufacturing across a distributed value chain, several practical limitations of the learning factory concept [1] have been identified as potential obstacles that arise to achieving its objectives. In this paper, we present an example of an expansion of an existing Model Factory value chain to another site in an urban environment, closer to the city centre. A Micro-Factory is developed in this new site that leverages smart manufacturing platform capabilities to enhance the existing value chain. In Section 2, we discuss the particular limitations of value chain manufacturing in the learning factory context that make this Micro-Factory valuable. In Section 3, we introduce the capabilities of the Micro-Factory in the City. In Section 4, we explain the resulting impact on the SIMTech Model Factory ecosystem, and conclude with a summary and discussion in Section 5.

2 Value Chain Manufacturing in the Learning Factory context

Apart from the challenges of resources and effectiveness that a learning factory faces [1], space- and cost-related mapping limitations are particularly salient to value chain manufacturing. These arise because of the difficulties of making the relevant levels of the value chain beyond the learning factory facility tangible to the learning environment and individual learners. While one way to bridge this gap is through approaches that consider extending the learning factory concept to global production systems [2], [3], the development of the Micro-Factory in the City is a different approach at leveraging the high connectivity and availability of an existing learning factory ecosystem to demonstrate actual multi-site value chain manufacturing.

To a lesser extent, the demonstration of the Micro-Factory concept also addresses the mobility and scalability limitations of a learning factory. While compatible with a virtual learning factory approach, such as in [4], due to its real-time data connectivity to the end-to-end production digital twin deployed in SIMTech, it is more directly designed as a mobile learning factory [5], maintaining the ability to enable last-mile

customisation capabilities and value chain manufacturing by only duplicating or transporting machinery that fits into a 20-footer shipping container. With connectivity infrastructure in place, this would allow the Micro-Factory to move or be copied to another desired location, even in an urban setting, thus further extending and leveraging the SIMTech and its value chain.

3 Capabilities of the Urban Micro-Factory

3.1 Remote visibility and management with real-time data connectivity

In order to enable and demonstrate distributed decision-making in the Model Factory ecosystem, real-time data connectivity is needed to ensure cohesive coordination across facilities in the value chain. In addition to 5G infrastructure which was added to all three factories in the SIMTech ecosystem, a common plug-and-play data collection platform was built to enable the low-code dynamic setup and configuration of data collection from various sources. The platform allows for flexible data collection setups by facilitating the seamless integration of data sources on the shopfloor and enterprise with applications at different layers. In addition, a suite of methods and programs was developed to handle real-time data processing tasks, efficiently mapping the data from these sources to target databases in applications.

With the data connectivity in place, the Micro-Factory is able to support a multi-site dashboard, which has been implemented in another Model Factory in the SIMTech ecosystem. This enables remote visibility into the Micro-Factory, while remote visibility from the Micro-Factory is likewise demonstrated on a customised dashboard, covering the three levels of supply chain, enterprise and shopfloor with the necessary applications that include logistics tracking, production and inventory tracking, and resource tracking across the value chain.

Figure 1 demonstrates the interactions between the various components of the value chain formed by the SIMTech Model Factory, Micro-Factory, industry partner, and other participants in the value chain. In particular, orders placed to the partner company on a social media platform (e.g. TikTok) can be customised in the Micro-Factory and sent via a 3rd party logistics provider to the customer without a physical flow from the industry partner. On the other hand, undifferentiated products (for customisation) are sent from the SIMTech Model Factory to the Micro-Factory. With the real-time data connectivity, decisions at enterprise and shopfloor levels can be made automatically based on the inventory levels, machine conditions, production schedules, and similar live data from the Model Factory and Micro-Factory.

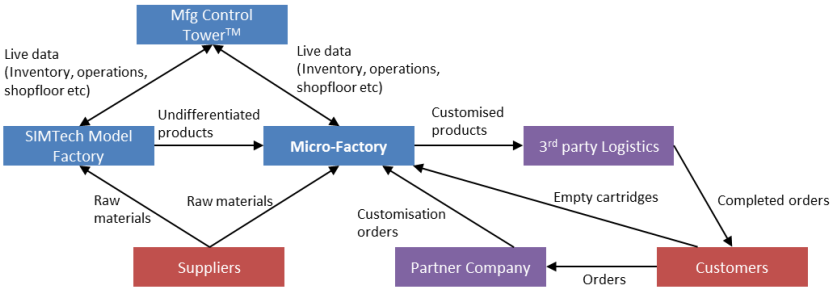


Fig. 1. Interactions between value chain components in SIMTech Model Factory ecosystem.

The Micro-Factory can also be managed remotely, with human input for production required only for restocking inventory and materials. A commercial Temi assistant mobile robot, with autonomous navigation, voice recognition, and remote-controlled camera capabilities was also added to serve as a remote tour guide. With this, learners and visitors in the Micro-Factory require minimal trained operators to be physically present, greatly reducing one of the key resource constraints of a learning factory.

3.2 Reconfigurable manufacturing cell with container form factor

The Micro-Factory manufacturing cell was designed to demonstrate the potential for rapid deployment of modular and mobile last-mile product customization capabilities that would belong in an urban production environment. To this end, the cell fits within the floor space of a 20-footer shipping container, with maintenance space included. It comprises two machines which cover a total footprint of 3.7m x 1.8m, with a total of four reconfigurable modules for holding inventory, assembly, printing and packing.

The machines communicate via OPC UA protocol and were designed to be compatible with the in-house software demonstrators, also deployed in the SIMTech Model Factory, for enterprise and shopfloor applications such as production planning and scheduling, real-time work order dispatch, and inventory analytics. These applications are layered on top of the Manufacturing Control Tower™ (MCT™) platform, which serves as a digital backbone for the Model Factory@SIMTech

The cell is low-emission and low-noise enough to be suitable for an office environment, with weight that does not require special load factor considerations. Its modules have been designed for one-process-family-product operations (instead of one-process-one-product), future-proofing it against the evolution of products both arising from co-innovation with industry, and from the operational and training needs of the SIMTech Model Factory ecosystem.

3.3 Closed-loop manufacturing considerations

The Micro-Factory, being a customer facing shopfront, features closed-loop manufacturing with a station for demonstrating end-of-life product collection and sorting. The sorting station includes an image-recognition module, paired with a cobot, such that the system can identify products returned, filter them from other extraneous items, and physically sort them into bins.

The image-recognition module can be easily retrained as products customised in the Micro-Factory change over time. The sorting station has also been integrated into the web-based order application in the Micro-Factory, so that customers can also claim credits at checkout for the returned items.

Using the Micro-Factory as a collection site is customer-centric and enables the first-mile collection of end-of-life products that is geographically close to the end-user or customer. This additionally balances the inventory and material flow to and from the Model Factory and the Micro-Factory to reduce the occurrence of 1-way trips, increasing the sustainability of logistics in operations.

4 Impact on the SIMTech Model Factory ecosystem

4.1 Testbed for value chain manufacturing

The Micro-Factory will enable companies to testbed value chain manufacturing technologies. In particular, the following technologies, currently in development under an ongoing research programme, will demonstrate proofs of concept in the Micro-Factory and across the SIMTech ecosystem:

(1) Decentralised decision-making capabilities under partial information visibility across the value chain,
(2) Flexible shopfloor through quick reconfiguration of equipment supported by AI-enabled adaptive few-shot learning capabilities, and
(3) Smart manufacturing platform technologies.

Decentralised Decision Making. While collaboration is desired, achieving complete visibility across partners faces challenges. Sensitive data like equipment health or production details are closely guarded, limiting full access. Current enterprise decision-making systems are centralised and typically deterministic, reliant on complete datasets [6]. Value chain partners will desire to retain autonomy over their decisions, such as accepting or rejecting orders based on profitability. Consequently, to support value-chain manufacturing, enterprise-level decisions, including inventory positioning [7], order management [8], or production planning and scheduling [9], must be decentralised and facilitative in nature, made with only limited data available to each partner. This shift requires novel AI-enabled algorithms that must be able to handle partial

information visibility in a decentralised manner, and also provide insights like profitability-to-promise (PTP), to enable value chain manufacturing.

Flexible Shopfloor. To enhance a production site's responsiveness to demand fluctuations, the shopfloor must pivot swiftly. This may involve adapting existing equipment for family-of-products usage instead of single-product only, incorporating modular features for quick changeovers. The shopfloor's flexibility can range from shopfloor level (e.g. layout reconfiguration) down to component level (e.g. adaptive end-effectors) [10]. Physical reconfigurability should be complemented by new digital capabilities being developed, including equipment reconfigurability assessment, flexible work order generation, and adaptive in-machine execution sequences in a cyber-physical production environment [11]. Novel AI-centric algorithms, learning from past batches, will enhance the quick stabilisation of the production line after reconfiguration, incorporating few-shot learning predictive quality and maintenance capabilities. This aids manufacturing companies in transitioning from a stable and static shopfloor to one capable of rapid adaptation to new tasks and orders.

Smart Manufacturing Platform (SMP). The SMP platform is designed to be versatile, deployable centrally or in a decentralised manner. It will feature real-time connectivity interfaces for timely (partial) information sharing, ensuring data accessibility only to the targeted recipient for specific intended usage, within stipulated duration. Unauthorized viewing or usage by both system and human users will be disabled.

4.2 Co-innovation with industry

Working together with an industry collaborator, the Micro-Factory has identified a hand-held liquid atomiser as its first product, currently in prototyping phase. The plastic injection-moulded components of the undifferentiated product will be manufactured in the other sites in the SIMTech value chain and sent to the Micro-Factory to showcase last-mile product customisation.

In the Micro-Factory, the atomiser can be customised with different liquids, different colours, and individual messaging, after which it is packaged for last-mile delivery. Our collaborator, using a social e-commerce and livestreaming model, will utilise the Micro-Factory to customise this product for commercial sales. With the reconfigurable manufacturing cell, the Micro-Factory will be able to support multiple such high-mix low-volume products, with the addition of suitable modules.

When deploying the Micro-Factory for commercial production, several practical aspects had to be considered to ensure that the collaboration would be successful. The key consideration was the viability of a multi-site, high-mix low-volume customised production business model for the collaborator. Steps that were taken to address this included:

1. Design of the reconfigurable manufacturing cell to ensure low cost of production while being able to meet the customisation requirements to attract customers.
2. Modular design of the software modules and dashboard to be compatible with the Model Factory with minimal re-programming.
3. Redesign of the product for flexible assembly and to use off-the-shelf circuit boards, reducing one of the main cost drivers.
4. Batching production orders where possible to reduce the logistics overhead and increase the sustainability of the Micro-Factory operations.

4.3 Immersive training and industry outreach

Other than enabling new content for workforce upskilling in the value chain manufacturing capabilities demonstrated in the Micro-Factory, it also shows the possibility of a more flexible approach to immersive training and industry outreach without bringing the learner or visitor out of the city centre. Along with hybrid and virtual training modules, the Micro-Factory does not need the development of detailed simulations to immerse learners and give them real-time feedback on their learning actions. This will increase the reach of training activities and tours conducted in the SIMTech Model Factory.

The Micro-Factory is also a suitable environment for training students and interns, as it provides a novel environment for them to develop case studies and software that are still applicable to the SIMTech Model Factory. Early uses of the Micro-Factory for this purpose have focused on generalising the existing training content and applications in the Model Factory to the specific operational context of the Micro-Factory.

5 Conclusion

Demonstrating value chain manufacturing in a learning factory context results in additional challenges. To enable distributed manufacturing and last-mile product customisation capabilities to be effectively shown, we have developed the Micro-Factory in the City concept and implemented it to extend the SIMTech ecosystem to a multi-site value chain producing a product in collaboration with an industry partner.

The Micro-Factory is mobile, suitable for an urban environment, and reconfigurable to take a family of products with closed-loop manufacturing considerations. It will, together with the SIMTech Model Factory, demonstrate proofs of concepts for value chain manufacturing, enabling deeper co-innovation with companies, immersive training, and industry outreach.

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