Urban Manufacturing of Sustainable Customer-Oriented Products

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Abstract. Personalization and sustainability are becoming driving forces to achieve a leading role in a fast-changing market. Therefore, manufacturers need to become more agile and flexible, introduce personalized products and customer-oriented services, measure and capitalize environmental intangibles. To answer to those requirements, this paper addresses the key elements characterizing the urban manufacturing concept, thought as an innovative production scenario leveraging closeness to customer, customization and sustainability. Such a framework is based on innovative technologies enabling collaborative short value chains and responsive production in constrained environments, for customer-oriented products and services. The main aspects, discussed in this paper, defining the proposed production paradigm are: (1) Product customization and digitalization; (2) Sustainability; (3) Flexible and short supply chain; (4) Responsive production systems; (5) Design to manufacturing in one step; (6) Industrial symbiosis; (7) open innovation. Two application cases in the furniture and footwear sectors are discussed, highlighting experienced benefits, open challenges and future research directions.

Keywords: Urban manufacturing · Mini-factories · Customer-oriented products · Responsive factories · Collaborative value chains · Sustainability

1 Introduction

Nowadays, customers demand more and more personalised products and services. At the same time, there has been a strong drive towards awareness of how products impact on the environment. To cope with this constrains, manufacturers have to (1) become more agile and flexible, in response to the fast rate in which market trends change, developing collaborative value chains and responsive manufacturing infrastructures that can produce higher variations in smaller quantities [8, 9], (2) introduce personalized products and customer oriented services whose added value can trigger market acceptance [11, 12], (3) measure and capitalize environmental intangibles (such as environmental pollution, local sourcing, waste and energy consumption) [2, 11].

As an answer to the aforementioned requirements, and to achieve a leading role in the fast-changing market, this paper addresses the key elements characterizing the urban

L. Monostori et al. (Eds.): AMP 2019, LNME, pp. 128–141, 2019.
https://doi.org/10.1007/978-3-030-18180-2_10

manufacturing concept, thought as an innovative production scenario leveraging closeness to customer, customization and sustainability as main drivers. Such a framework is based on innovative technologies enabling collaborative value chains [8] and responsive production plants [9] for customer-oriented products and services [11, 12].

This paper first addresses the main features of the proposed innovative urban production framework in Sect. 2. Then, two industrial application cases are discussed with reference to the furniture and footwear sectors in Sects. 3 and 4 respectively. In Sect. 5, an analysis of the two the application cases is performed highlighting the experienced benefits and the open challenges. Finally, some concluding remarks as well as future research directions are outlined in Sect. 6.

2 Key Elements of the Proposed Urban Production Framework

An urban manufacturing system is defined as a production system located in an urban environment that is actively utilizing the unique characteristics of the surroundings towards value creation for the customer [1]. Further to that, we explore the idea of urban manufacturing through mini-factories (Fig. 1), where the reduced dimension is cornerstone to place the factory directly where the customer is used to live and go shopping, revolutionizing the way products are designed, produced and sold. The urban mini-factory is meant to embody the concept of "close to the customer" in terms of features offered, place of fabrication, time to deliver and sourcing of materials. The main aspects defining the framework of the proposed production paradigm are outlined in the following points:

1. **Product customization and digitalization.** Customers are integrated into value creation by defining and configuring an individual solution, concretizing needs and desires into concrete product specifications (and later driving manufacturing). As far as production in mini-factories is concerned, the digitalization of the products and of the customization processes is a key element because of two main reasons: first, the concept of personalization itself, coupled with space constraints, basically limits the capability to experience physical products down to zero. Digitization turns a non-existent physical product into a digital customer experience to create competitive difference and drive engagement. Second, the digital customization process is an action that concretizes the personalization potential into a single customized product, with well-defined specifications ready to be seamlessly transformed into manufacturing operations [2].
2. **Sustainability.** The label of "sustainable" is a bottom line requirement: as a matter of fact, sustainability has become a common basic goal for many national and international organizations and a driver for customers' choices. Indeed, being sustainable is a picklock for accessing most demanding customers. However, in spite of the nearly universal recognition, people still struggle with the full understanding of the concept. The urban mini-factory must propose practical indexes to build-up an effective assessment model, to reflect in real time the impact of customer choices during his shopping experience. This evaluation represents a

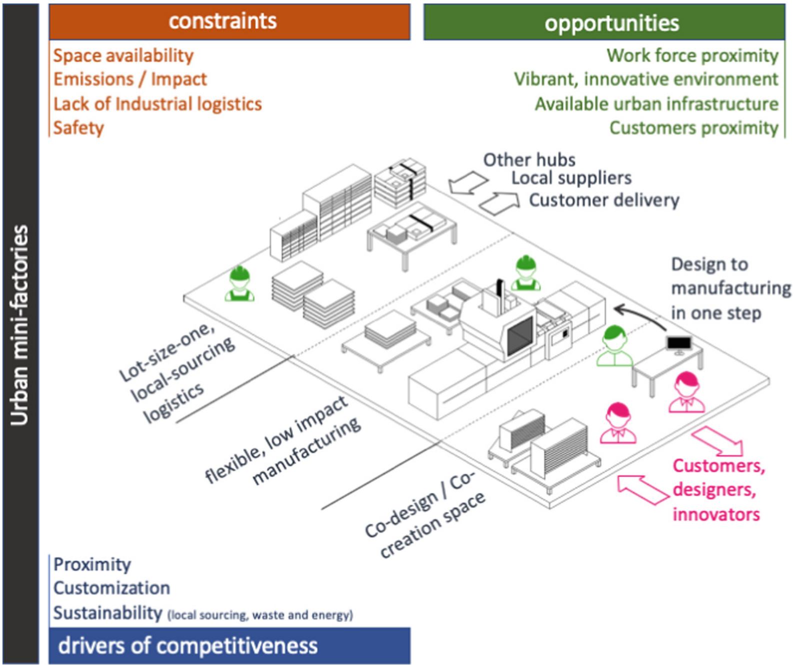

Fig. 1. The urban mini-factory framework: drivers, constraints and opportunities.

quantitative measurement of environmental, and possibly also economic and social performances: the use of concrete figures and quantitative evaluations transforms the well-recognized, but sometimes vague concept, of sustainability into a powerful tool that customer can understand and apply to guide their choices, further highlighting the attractiveness of the urban manufacturing paradigm [3].

3. **Flexible and short supply chain**. Even if an urban factory, by being situated close to the workforce, potential customers and suppliers, can take advantage of the urban infrastructure, logistical challenges are still commonly seen as one of the most demanding obstacles to urban production, particularly when considering the needed on demand and just in time supply chain features [4]. On the other hand, this notwithstanding, short and local (like "farm to table" concept) distribution channels could be an essential driving force towards value creation for the customer. Therefore innovative collaborative value chains are a major driver to enable the proposed concept [8, 11].
4. **Responsive production systems: low impact; safe; flexible.** To enable urban production, it is necessary to adapt standard manufacturing technologies to urban requirements, in terms of emissions, high flexibility to match customization requirements (the manufacturing system will need to ensure the execution of all the fundamental processes required, measured against the space available), and safety [5]. In particular reconfigurable [9] and highly automated production systems [10]

are needed to properly and effectively respond to the customers expectations, thus requiring novel machines and control solutions.

5. **Design to manufacturing in one step.** Tools and post-processing technologies, able to remove any software exchange and machine programming complexity, are needed to empower quick and highly automatized manufacturing of personalized goods. Once the product is configured, the design needs to be processed and transformed into machine-ready language on one side, and enterprise resource planning data on the other (to trigger the supply chain) [6]. To achieve such objectives advanced CAD-CAM as well as MES tools have to be introduced, supporting innovative post-processing and scheduling methods [8].
6. **Industrial symbiosis.** The socio-economical-technical constraints rooted in the urban manufacturing concept will call for a new set of a wide-ranging interaction among companies, also participating in diverse and collaborative value chains, in order to optimize the use of energy and other critical resources, such as water, materials (both raw and recycled), residues, etc. The beneficial reuse of flows (water, waste, by-products, energy, recycled materials, etc.) results in a more resource-efficient production at network level, and in fewer adverse environmental impacts: this is of the uttermost importance taking into account the urban environment in which the mini-factories operate [7, 12].
7. **Open innovation.** Potentially, an urban manufacturing system actively utilizes the urban society and the knowledge and skills of the citizens. This has the prospective to radically change the traditional logics, currently in place to design and manufacture products, towards an increased open-oriented approach for customers and value chain actors, to collectively develop and make personalized products and services, integrating digital-led innovative features and exploiting a dynamic and dispersed production ecosystem. The potential of the collaborative and networked innovation resulting from a high level of diversity can be exploited, for the benefit of the consumer, as well as for the benefit of the industry.

3 Application Case in the Furniture Sector: The CTC Project

The Close To the Customer (CTC) mini-factory is a production scenario exploiting closeness to customer, customization and sustainability in order to strengthen the competitive position of manufacturers in the furniture market. The idea of CTC is to move the factory directly behind a glass panel in the shopping mall (Fig. 2), making closeness to the customer and purchasing experience at the centre of the whole value proposition [13].

The CTC mini-factory finds its ideal location in a shopping mall where both the sales area and the production area are located next to each other and are accessible by people visiting the mall. The CTC mini-factory scenario begins with a customer entering the CTC shop and customizing the furniture he/she is interested into, using a user-friendly configurator. The design of furniture is driven by a parametric portfolio of products that has been predefined by CTC designers coherently with the functional constraints of the mini-factory. Once the furniture project (a single piece of furniture or

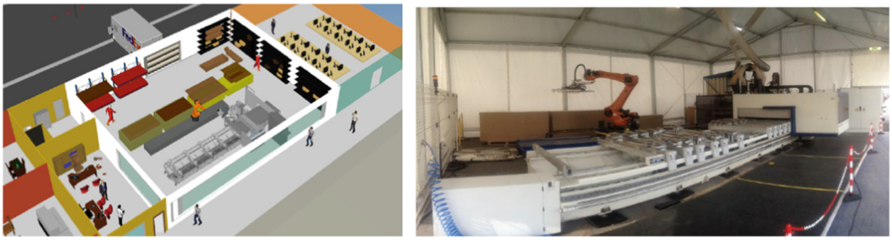

Fig. 2. The CTC urban manufacturing concept: scenario and real machining system.

a complete room) is finalized and the customer is satisfied with the offer, an order is generated and sent to the CTC-factory. Machine instructions are automatically created to command the behaviour of the mini-factory. A real-time update of production data allows the customer to monitor the processing status of his/her order other than to increase the efficiency of the production system itself. A high level of integration of informative systems is one of the main features the CTC-system. In fact, a smooth flow of information from the idea generation to the production allows a lean fulfilment of orders in short times.

Product Customization and Digitalization

CTC manufactures personalized furniture that can be configured in terms of colour, material, dimensions and shape. A dedicated basic design tool enables to define, starting from scratch, the parametric products compatible with CTC production system requirements and constraints. The tool is meant to support designers during the creation of the stable solution space characterizing the CTC products' portfolio. As output, the software develops a parametric product library that will be used, in the CTC configurator, as starting point for the creation of personalised product designs. By simply feeding the customization requirements through a tablet-based user interface, the design can be thus adapted, automatically updating price and specific sustainability impact of the configured product at each iteration.

Sustainability

CTC deliveries a green label, based on the concept of product footprint and the related life cycle analysis, used to give the customers the means to understand the impact their products and customization variants have on a set of sustainability indexes [14, 15]. In order to obtain this information, an assessment engine was built to retrieve the data related to material of the components, operations performed and environmental indicators of the material suppliers, and transform them in product related impact data. The assessment is meant to enrich the report sent to CTC customers after product configuration and prior to product delivery in order to increment the value-added proposition perceived by CTC consumers. The customer can thus know the environmental performances related to the configured product and, varying its configuration, can determine the best product both from the esthetical, technical, economic and environmental point of view.

Flexible and Short Supply Chain

In order to cope with product customisation needs, CTC requires an high level of flexibility in the upstream supply chain, enabling to achieve the required level of service that the business model propose (one week delivery). To meet this requirement, it is of primary importance that the CTC Mini-factory panel suppliers are distributed locally, which means at a distance around 20 km. This is intended to enable delivery of panels each 2 days, thus limiting the number of panels to be stored in the mini-factory near to zero, and enabling to maintain a greater variety in the type of materials and colours to be offered.

Responsive Production System: Low Impact; Safe; Flexible

The production of furniture within the CTC production system is carried out by an innovative manufacturing cell designed to withstand customized products manufacturing according with requirements of high automation, flexibility and safety [16]. The machining centre is able to ensure the execution of all the fundamental processes required to work wooden laminated panels: nesting, boring, routing and edge-banding, all in a single machine [17]. The process of furniture realization is fully automated thanks to the integration in the system of an anthropomorphic robot able to pick raw panels from stacks nearby the working centre and to position them on the machine worktable. The developed manufacturing cell is able to withstand customized product manufacturing requirements by providing (i) a high degree of flexibility for batch size 1 production; (ii) high degree of automation thanks to inclusion, in a single system, of all the functions (nesting, boring, routing, edge-banding) required for panel based furniture manufacturing; (iii) integration of simplified and optimized machine interfaces and safety equipment supporting machine supervision by means of a single worker; (iv) optimized dust extraction capabilities supporting near-zero production of wooden dust for installation in a not industrial context. Eventually, a reduced foot print area is obtained thanks to a compact lay-out able to include machinery, loading/unloading system, tools and edges warehouses and panels' stacks in 120 square meters.

Design to Manufacturing in One Step

The CTC scenario puts in place all the constitutive elements of a streamlined design to manufacturing procedure, enabling the transition from the digital avatar of the product to the real one, in a fully automated fashion [18]. Once a configuration is completed, the configurator translates the "design language" in machine readable language by means of a post-processor. The post-processor, developed in tight collaboration with the developers of the CTC production system, generates the scripting files required to re-tune the manufacturing system according with the customized characteristics of each product and to guide the manufacturing operations. For instance, the post-processor guides the nesting operation, intended to enable the minimization of the scrap rate and understand the raw material to be communicated to the ERP for raw materials order. Through the connection with the production system supervisor, the overall manufacturing time required to bore, mill, cut and edge-band all sheets is eventually calculated and used to evaluate the precise delivery date to be returned to the customer. The connection with a dedicated scheduler enables to generate and store the tasks required to manufacture the defined furniture. Considering the estimated raw material arrival date and the expected manufacturing time, the scheduler is able to define a production queue, thus empowering the expected manufacturing date that is eventually delivered to the customer.

Open Innovation
The nature of a business relying on digital designs opens-up several opportunities in terms of distribution and openness of the design community [19]. In CTC, the involvement of an open community of designers residing in a location potentially remote with respect to the CTC mini-factory, is considered a value adding element enabling to increase the number of design product to be offered and supporting the granularity of design styles. In a franchising-based scenario, as one of those conceived in CTC, the product portfolio will be kept updated, with new releases determined by the setup of the franchiser, validating and industrializing the proposals coming from the open community of designers.

4 Application Case in the Footwear Sector: The ADDFactor Project

In the footwear sector, consumers demand for personalised, comfortable, safe-healthy, affordable and sustainable products is growing. This is a traditional pillar of value-added manufacturing, targeting products recognized and considered as a reference all around the world [20]. To meet these demands, ADDFactor (ADvanced Digital technologies and virtual engineering for mini-Factories) proposes a "Mini-factories"

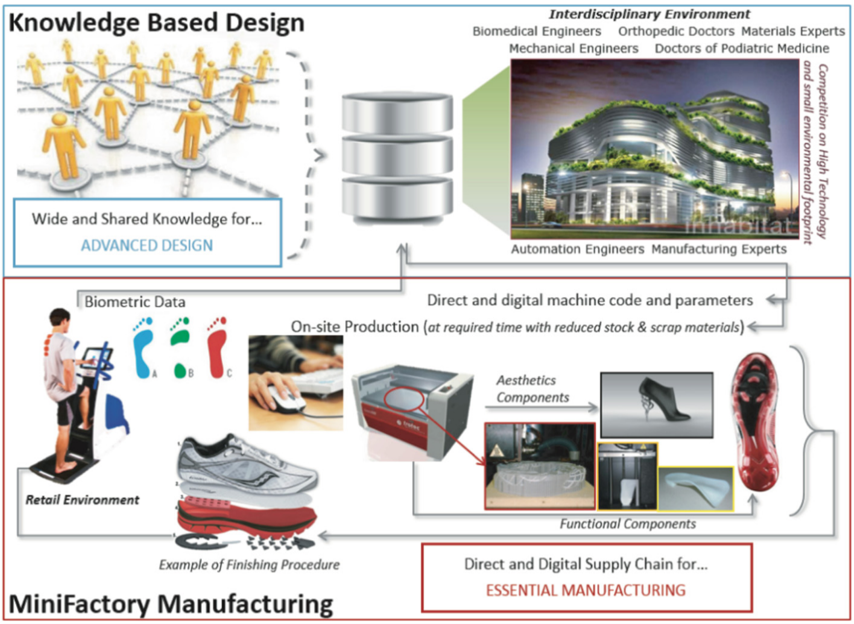

Fig. 3. The ADDFactor urban manufacturing concept.

concept, which is conceived to be an innovative solution for most of the actors involved in the whole supply chain: the link between retailers and the manufacturing technologies is supported by a new production framework concept, which is based on central knowledge-based design and local distributed manufacturing in mini-factories (Fig. 3).

This concept is applied focusing on need-driven products, where the functional personalisation along with the aesthetic customization become important assets to claim a direct relationship with the users of those goods. ADDFactor manages the complexity of the design phase thanks to a direct connection with the retailer, that provides "biometric data" of the customers as tacit requirements and "aesthetics tests" as explicit demands, being both fundamental for an effective individual personalization.

ADDFactor provides all the technologies needed to manage two typologies of data: the acquired *biometric data* as input for designing custom solutions and the *technological parameters* as output of design phase, necessary to drive the machines (in retails or near environments) to fabricate advanced products. In the retail, final users may personalize the aesthetics of products and the collected requests are then sent and automatically linked to the acquired data necessary to manufacture locally the products through an easy-friendly configurator.

ADDFactor provides manufacturing solutions which are placed at retail environment. At the end, the retails have all the acquisitions technologies necessary to collect the data, fabricate the complete product (such as foot orthotics), finalize a custom solution with the production of personalized element (such as heels, plateau and insoles) assembling them on standard products.

Product Customization and Digitalization

ADDFactor develops customized shoe's components (functional, bio-medical and safety-wellness related aspects), so as to guarantee comfortable, performing, safe and healthy products for different application (orthopaedic, sport and leisure and fashion) and different consumers, mainly biometric customization with aesthetic possibilities. In the retail, advanced shoes design configurators empower the final user to access and personalize the product, targeting necessary information gathering related to:

a. **insole based solutions:** the customer can select the desired upper part of the shoe from a set of available parts and the colour of the sole. The geometry of the sole changes according to the individual biometric data.
b. **fashion shoes:** in this case the customer can mainly customize aspects like the heel shape (geometry of the heel), the texture and the colour. Moreover, the customer can select the desired upper part of the shoe from a set of available parts.

ADDFactor products, accompanied by the biometric characterisation of user, are fully digitalized in order to support: (i) basic design of customizable products by means of ad-hoc created CAD applications and configurators; (ii) musculoskeletal analysis (iii) adaptive and auto-configurable local flexible production.

In order to support the biometric characterization of the customer, ADDFactor provides low-cost, precise, robust and easy to use scanning devices (such as 3D scanner, pressure distribution sensors device and inverse kinematics detectors) which allow the treatment of an important amount of biometric data and eventual relative product preferences. Those scanning technologies overtake the limits represented by the available technologies in application for commercial usage in local stores and detect biomechanical aspects of customers in order to drive the design phases of final products.

Responsive Production System: Low Impact; Safe and Flexible
As it is obvious to know, all the techniques such as vacuum forming, machining and hand-finishing produce orthoses that are not reproducible and difficult to verify or control for quality and functionality [21], they should leave the way to some other techniques able to use that complex data and confer major functionalities to the final product at reduced cost.

ADDFactor is mainly focused on subtractive and additive techniques which represent the most important rapid, flexible and low-impact manufacturing technologies. While the first one uses a conventional technique to remove the excess material, producing waste materials, the second one is a non-conventional production based on layer by layer manufacturing. In this case, the process which starts easily and directly from the digital file (treated and converted in standard format), allow an "essential" manufacturing through a faster and more repeatable procedure. Whereas the additive machine is more focused on rigid-semi-rigid materials and it is able to produce with a reduced volume of waste materials, the NC machines are more recommended to manufacture flexible materials which are obtained by conventional chemical procedures which guarantee the requested thermal and mechanical properties. The main effort of the additive manufacturing is mainly focused on developing dedicated and optimized solutions for flexible manufacturing of target products [22, 23].

In the milling machines operation, the complexity of shape, such as the bottom of the foot, is converted into three-dimensional trajectories in the working volume which are anytime calculated by CAM software and post-processed for the machine controls. The milling tool which follows "alone" the instructions going around in the 3D volume, is replaced by a dedicated layout of multiple tools which receive direct data to be implemented being auto-configurable and guaranteeing an ultra-fast milling operation which is finalized by one or two passages of the product under the multi-tools. This machine is mainly used for producing accommodative insoles, but the evolution proposed by ADDFactor allows a repeatable and industrial way to produce anytime personalized shape. The improved speed and easy-friendly con-figuration makes the approach suitable to provide insoles to the mass market along with normal shoes which already let customers to insert external and personal insoles.

All the ADDFactor machines considers the environmental aspects, in terms of ecologic and reusable materials (bio-degradable materials for sole, reusable and recyclable materials such as thermoplastics for extrusion-based machines). Moreover, the extrusion-based process neither uses toxic polymers nor causes smoke or fumes during the deposition. The fabrication is per-formed safely, allowing the installation of machinery and systems in office environments without health risks.

Design to Manufacturing in One Step
The biometric characterisation of the customer, accompanied by customer's personalization choices, drives the manufacturing process, thanks to CAD-to-Printer capability provided by the ADDFactor framework.

The motion and forces detected by the acquisition devices can be translated to understand the joint reaction forces and other data in order to develop foot personalized orthoses for better functional performance and comfort. The complex foot model interprets and simulates the input data being able to process dynamic external forces in order to define the optimal product specifications.

The data interpretation and simulation are performed by the ADDFactor design tools, provided for the engineering of the products, resulting in the creation of complex internal structures (meso-structures) and profile within the functionalised product, to be realized via rapid/additive manufacturing.

Management of the resulting complex structured product is then carried out at production level: data on product internal structure are handled and post processed so as to create a direct self-contained digital part program, comprehensive of all needed information to be manufactured at retail level, by means of ADDFactor production technologies.

Open Innovation

ADDFactor supports an open design community enabling the creation of new parts of products (for example new heels for fashion shoes or new textures for sole and insoles) compatible with the ADDFactor production framework. The involvement of an open community of designers represents a big opportunity for the ADDFactor framework because it enables to increase the number of design parts to be offered and proposed to the final user. This community can be widely spread, based on a single repository and accessible to each ADDFactor mini-factory instance obtaining, as final result, a value-added service.

5 Experienced Benefits and Open Challenges

Through both the presented application cases, the following major benefits have been experienced.

- **Customers involvement and satisfaction:** CTC underwent validation through the implementation of the mini-factory in a real the shopping mall. Customers involved in the demo activity have been able to experience the whole CTC concept, from configuration to manufacturing and delivery of customized product. In particular, more than 50 real customers have been involved in the configuration and manufacturing of customized furniture. The general satisfaction of the customers involved in the CTC process has been very high, with a particular mention about the flexibility of products' configuration. AddFactor shoes have been extensively tested with semi-professional runners, that evaluated through questionnaires the following aspects: comfort, weight, flexibility, medio-lateral stability, fitting. The customized shoes achieved good overall performances (including the perception of the customization process), this notwithstanding some critical issues that have been noted in the upper-tongue flexibility and sole edge rigidity.
- **Reduction of value chain and production times and cost*s*** have been experienced in both projects. As an example, within the CTC validation activity, the average delivery time was 2.23 Days, throughput was 0.5 orders per hour (development of

customized cabinets), and inventory level (measuring the number of days the factory can produce without replenishment) was 4 days. Nowadays, the average delivery time for customized furniture, manufactured within standard value chains, is today around 3 weeks.

- **Increase of sustainability performance:** the green label is designed to communicate to the customers the sustainability of the overall production processes and the impact of his customization choices as far as the considered products, i.e. furniture and footwear products, are concerned. As an example, in the CTC project the LCA analysis was based on a comparison with a piece of furniture, produced with wood not coming from a certified supply chain. CTC products showed a general reduction of production related impacts on a set of 5 impact indicators, with an average reduction of 150% of CO2 emissions in the demonstrated scenario configurations.
- **Open innovation of products and processes** have been developed and assessed in the mentioned application cases of the proposed urban manufacturing framework. In the AddFactor project open innovation of products has been enabled through the design and manufacturing of customized shoes components, by means of different production technologies and solutions. In the CTC project, a set of industrial design students have been also involved in new furniture design for CTC products. The students proposed creative ideas that were included into the catalogue, offering, on the one hand, visibility to young designers, and, on the other hand, additional personalization options to the CTC customers (that also provided feedbacks). This approach has the potential to unleash creativity of designer towards co-creation of new pieces of furniture: this potential hardly finds today its way through the rigid structures of the furniture industry that is often based on a closed innovation approach. Thus, the project allowed democratizing the access to production resources in the furniture sector, towards increased capability to discover talents.

In order to fully implement the proposed urban manufacturing framework some major innovation challenges have to be tackled in the near future. In particular the main elements to be addressed are shortly addressed thereunder.

- **Open product co-design methods and tools** have to be developed, based on innovative and modular product development methodologies as well as on collaborative digital solutions.
- **Advanced post-processors** to shorten the design to manufacturing time and minimize human intervention are of major relevance in order to support on demand production of personalized products, specifically to properly integrated novel advanced CAD features with advanced CAM tools for CNC based flexible machines.
- **Reconfigurable, low impact and safe machines** are of crucial importance, with specific focus on their capacity to effectively produce a larger variety of products and/or products components.
- **Responsive and clean factories** integrating agile automation and real time scheduling capacities are needed to cope with the requirements of the proposed urban manufacturing framework, and to properly respond to the customers expectations.

- **Reactive and integrated value chains** are mandatory to guarantee the just in time and on demand production capacities needed to fully implement the proposed and discussed urban manufacturing framework.

Real time and effective LCA tools have to be further developed so as to support the sustainability oriented customer involvement in the product and process co-design.

6 Conclusion

Urban manufacturing is an innovative concept that leverages the production of sustainable customized products, manufactured and sold directly within the urban environment. This is meant as a strategic business model to support manufacturers in innovating products and services value chains. This paper addresses the main aspects defining the framework of this production paradigm and presents two application cases in the furniture and footwear sector, pointing out their benefits.

The implementation activities carried out in the two use-cases, briefly described above, showed how the urban manufacturing concept can be actually instantiated in a real urban context, involving customers that have been able to experience the whole concept by configuring, see manufactured and receiving their customized products. The quantitative and qualitative results obtained during those instantiations are promising and pave the way for further research: customers involved in the experience strongly supported the freedom of personalization, the sustainability aspects, and the short delivery times, demonstrating the actual feasibility at larger scale.

Future work will concern methods and tools for customers involvement through co-design instruments, flexible and clean machining centers for urban production, digital solutions for personalized production operations and planning, just in time and on demand value chains management solutions, novel sustainability assessment tools.

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