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Open and Circular Value Creation in the Open Micro Factory

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01 Introduction

Recent environmental, economic, and societal instabilities such as the climate crisis, disrupted supply chains and the rising global social inequality pose new challenges, especially for today's global production systems. Factories as places of value creation through processing materials to components and products with the use of production means, information and energy, contribute significantly to the consumption of earth resources (Marchi, 2022). Set climate goals are unlikely to be achieved and carbon dioxide (CO_2) concentration which represents a control parameter of the planetary boundary framework is already in its limit range with the forecast of an increasing risk (Rockström et al., 2009; Climate Change: Atmospheric Carbon Dioxide). CO_2 emissions, particularly, depend directly or indirectly on the global production networks and their, so far, unsustainable operations. Furthermore, the UN Sustainable Development Goals (SDGs) address the need of a transition in production systems with goal 12 „Responsible Consumption and Production“:

„Goal 12 is about ensuring sustainable consumption and production patterns which is key to sustain the livelihoods of current and future generations. Unsustainable patterns of consumption and production are root causes of the triple planetary crises of climate change, biodiversity loss and pollution. These crises, and related environmental degradation, threaten human well-being and achievement of the Sustainable Development Goals.” (United Nations Sustainable Development)

Thus, there is a need of rethinking our current value creation system, especially, of its factories as elementary components. New concepts and models should consider existing industrial production infrastructure as well as new bottom-up production approaches as seen within the maker movement where new innovative methods are designed and show great potential for adapting our current way of consumption and production (Hildebrandt et al., 2022).

Concepts proposed in the literature for sustainable factory units are tightly linked to the concepts of circular, sustainable, and changeable manufacturing systems as a superordinate system layout (Acerbi & Taisch, 2020). Concepts of Industry 4.0 and cyber-physical production systems make use of the digital sphere for data processing, monitoring, automation, and validating actions of adoption (Schmitt, 2017; Hästbacka et al., 2022). These concepts present possibilities to keep the value creation cycles geographically minimal while at the same time maximizing the energy and material efficiency using data-driven monitoring and control.

Most production systems are based either on small workshops, labor-intensive processes, and low output levels, or on large factories with standardized, capital-intensive processes and high output levels. These poles leave a large gap between very low production volumes (hundreds of units maximum) and very high production volumes (millions of units) (Montes & Olleros, 2019). On the factory level, micro factory concepts with existing subsets of urban and local micro factory concepts are therefore presented (Hildebrandt et al., 2020; Herrmann et al., 2020). Open Labs contribute to citizen education, innovation and peer-to-peer production in the area of local, bottom-up based value creation from which sustainable, socially fair and resilient solutions emerge (Redlich et al., 2015). Especially through the use of open source methods, new forms of collaboration, community-based and bottom-up approaches both, on a socio-economical and technical level take place (Bonvoisin et al., 2020; Omer et al., 2022, Blind et al., 2021)

The mentioned concepts in the field of industrial production continue to leave out the social factor in terms of participation of locally influenced actors where factories are embedded. Also, the criteria of optimizing production processes are dependent on ownership rights of production means and non-transparent decision making structures. However, Open Labs and the respective makerspace infrastructure cannot meet the current production demand. They also lack concrete concepts for products with higher complexity and quality. Therefore, a technological as well as operational enhancement of current Open Lab concepts is required that is oriented towards existing sustainable and circular production concepts by still keeping its character of openness, co-creation and collaboration.

The goal is to develop a concept for a micro factory that integrates the current state of the art and best practices from industry on the one hand, but also takes into account methods and technologies of Open Labs, open-source software and hardware to present a complementary production entity that is locally integrated and provides a contribution to the transition to a regenerative and circular value creation system.

This paper introduces concepts on circular manufacturing, micro factories, industry 4.0 and open production, then describes the OMF concept with its scope and a high-level architecture layout and closes with a conclusion and discussion for further research.

02 Theoretical Background

Circular and changeable manufacturing

Circular manufacturing is described as an overall system framework for closing the loop of product life cycles through multiple usage of components and materials, preferably in their original form. Therefore, a systematic perspective on the phases of production planning, supply-chain configuration, manufacturing, delivery, use and recovery and reuse is needed. Not only within the physical product and production level, but also on the service level which includes the provision of complementary product-service systems. The aim of this resource circulation is to reduce the total amount of resource usage while raising the environmental efficiency of resource usage (Shi, 2021).

A systematic multi-method model and simulation approach introduced by Roci et al. (2022) provides different layers of modeling including agent-based, discrete-event and dynamic system model domains for each stakeholder of a value creation system such as customers, service providers, manufacturers, and recyclers. For a manufacturer stakeholder, a machine operator as an example represents one type of agent who has the knowledge and the skills to participate and interact within the circular manufacturing system. The dynamic and discrete-event model types are more technical process-centric methods to model process behavior over time or asynchronously occurring events like a machine fault or finished process step. The management of data is described within an information system (Roci et al., 2022).

Complementary to the circular manufacturing system is the topic of changeable manufacturing systems which are described by El Maraghy & Wiendahl (2009) with their capability of flexibility and changeability to address the production of a higher spectrum of products. Changeable manufacturing systems accomplish early and foresighted adjustments of its structures and processes on all levels in an economically feasible way. A first set of changeable manufacturing characteristics is: Changeover ability on process and machine cell level to manufacture ad-hoc different variants; Flexibility on system level to manufacture different products by reprogramming, rescheduling or rerouting; Reconfigurability on system level to prepare for changing volumes of new products and returned, used products by adding, removing or changing modules in the system; and Transformability to change the manufacturing structure significantly to produce an entirely different product type (Brunoe et al., 2018 & 2019).

Urban Factory and Micro Factory

The VDI guideline 5200 defines a factory as a "place where value creation takes place through the division of production labor of industrial goods using production factors." The production factors are the required operating resources, materials, energy, information and personnel. Factories are referred to as socio-technical systems due to the complex interplay of production factors. (VDI 5200)

A specific factory concept for urban space is the Urban Factory (UF), which is defined as a factory in an urban environment that actively uses the characteristics of its surroundings. The UF has a minimal negative ecological impact on its quarter by minimizing emissions of, e.g., sound, smell and traffic load while positively influencing the local economy by increasing demand for jobs, social-economic interaction and innovation fostered by an urban factory (Herrmann et al, 2020). As a first typology regarding characteristics, potentials, and challenges of transition zones where an urban factory is embedded in an existing socio-ecological environment, the concept of ecotones for sustainable value-creation is presented by Juraschek et al. (2018)

The term micro factory in contradiction to older publications does not refer to minimizing the machining size and matching it to the part size of a micro-part-industry (Herrmann et al, 2020). It refers to the concept of highly modular, flexible and automated production facilities with a relatively low spatial footprint (Hildebrandt et al, 2020). Montes & Olleros (2019) describe further characteristics how micro factories can stimulate local and demand-driven innovation to address the need of local demand-driven fabrication as well as the central role of digital technologies with digital sensing, simulation and the use of computer-aided design and manufacturing software in micro factories.

Cyber-Physical Production Systems and Industrial Internet of Things

For data-based circular economy approaches, data-driven circular manufacturing system models need to be linked with physical infrastructure entities like a factory. The term Cyber-Physical Systems (CPS) was introduced by Helen Gill at the National Science Foundation workshop in 2006. A CPS describes the integration of computer calculation in physical processes influencing other physical processes providing sensored feedback signals and thus connecting the physical and information technology world. CPSs arise as a result of the networking and integration of embedded systems and application systems. Schmitt et al. (2017) summarize a CPS as a physical system with data storage, data processing and extensive communication interface features which increase the level of local system intelligence.

With a special focus on production-related processes, the term Cyber-Physical Production Systems (CPPS) evolved and considers the product, the production and the production system. It provides the opportunity to allow methods for Plug and Produce capability. A CPPS supports autonomous self-monitoring and helps to receive a self-organizing adaptable production. Standardization and modularization play an essential role as they allow a network-wide connection of entities within a CPPS (Schmitt et al., 2017). A CPPS can exist out of more CP(P)S entities connected in a hierarchical, decentralized, or distributed communication topology with several subsystems which makes it a system in a system (SoS) model type comprising physical processes, models of software and computation frameworks and networks (Putnik et al., 2019). CPPS includes, thereby, the current industry concepts and applications in the field of Industrial Internet of Things (IIoT) or Industry 4.0.

Within CPPS entities, the use of factory automation and data management technology is crucial. Therefore, Raptis et al. (2019) and Brecher et al. (2021) give a comprehensive overview of key technologies and services which enable the potential of networked industrial systems reflected on the existing industrial automation pyramid model. For this paper, the most relevant fields rely on Machine to Machine (M2M) communication, automated robots (which includes computer numerical controlled (CNC) machines, (automated) assembly lines and (wireless) networked control systems (WNCS) on the control and periphery layer which is directly connected to the given physical production processes within the CPPS entity. On the supervisory and data acquisition layer, based on top of the control layer, with more data-centric, service-oriented methods, there are job scheduling, decision making, anomalies detection and fault diagnosis as well as energy management. Within the multi-entity networked cloud-based layer, technologies like big data analytics as well as ontology and semantic-based methods provide machine learning capabilities within defined use-cases and data spaces.

Open Production, Open Labs and Open-Source Hardware

The concept of open production comprises comprehensive value creation systematics, describing new forms of value creation in a bottom-up economy in which collaborative, distributed and self-organized interaction between individuals or organizations takes place during all phases of value creation. The principle of openness, which describes the open interaction of subcomponents within this system, is an essential element of the open production framework (Redlich & Wulfsberg, 2011). Openness in terms of knowledge and information components is developed under the terms of free and open-source software (FOSS) and open-source hardware (OSH). The Open Source Hardware Association (OSHWA) defines open-source hardware as follows: “Open-source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design.” (OSHWA, 2022).

Openness in terms of production spaces is represented in Fab and Open Labs. These are places where access to production infrastructure in the form of digital controlled machine tools like 3D printers, laser cutters and CNC mills is provided to the local community. With this access they are able to learn and innovate about new product design, prototyping and production methods developed in a bottom-up and problem-oriented manner. Fab and Open Labs offer a space for self-organized and collaboration-oriented projects and contribute to an increased participation of the local community in value-creation processes (Basmer-Birkenfeld et al., 2015). Redlich et al. (2016) characterize a new production system on an Open Lab Micro Factory level with robustness and wear-resistance, minimal capital and operating costs, low precision, flexibility and adaptability, standardized machine parts and products, basic raw materials, small spaces and high movability. Recent research by Buxbaum et al. (2022) describe an urban living lab approach in the context of open, distributed manufacturing (ODM) executing cosmo-local peer-production.

03 The Open Micro Factory Concept

The developed concept of OMF shall provide a first basis for a model-based system design of micro factories in the context of open and circular production. The focus is on the ability to provide a data-driven factory entity in a local production network. All capabilities required for circular fabrication shall be covered with additional focus on end-of-life product handling, material recycling and reconfiguration of OMF settings as well as data monitoring.

Context and scope

The goal is a regenerative circular value creation system with minimal global dependencies regarding the flow of goods, material, and energy. The OMF concept functions as a complementary component to the existing industrial as well as open lab infrastructure. Therefore, Hildebrandt et al. (2020) introduced a hybrid concept, a space between the maker movement and industrial production. The space is spanned in 4 dimensions: production depth, technical capabilities, and production quantity and quality. At one pole, industrial production with a high number of quantities, quality as well as high production depth and high-end technical capabilities. The other pole marks makerspaces with low quantity, low quality, low production depth and simple digitally controlled machines and hand tools.

The concept of OMF introduces a hybrid manufacturing facility that aims to fill the gap between the makerspaces and industrial production to allow medium production volumes and product complexity, medium to high quality standards, medium production depth and a medium to high capability spectrum. In addition, the OMF can be set up either as a new building or integrated into existing infrastructures, thereby, being constructed minimally invasive and with low effort. By integrating into existing spatial structures, a maximum symbiosis with external systems shall be achieved.

Due to the high modularity and flexibility of the OMF, the production processes in the OMF should be designed according to the principle of elementarization (Redlich et al., 2018). Elementarization describes the decomposition of the production process and system into elementaries, i.e., into the smallest sections of product creation of low complexity. These production elements are designed as simple, self-centering systems that can be operated intuitively and are highly robust due to a minimal need for control. The connectivity between the workpiece and the production elementary is designed to allow the creation of ad-hoc machining spaces. The elementaries are encapsulated systems, this procedure allows them to be combined in any way to form process chains.

Demand-driven and service-oriented operation

The OMF is intended to produce according to local demand for products and then allocate its available resources to this demand. Therefore, the OMF is providing manufacturing and machine-as-a-service capabilities to any entity within the local value creation network, e.g., individuals, organizations, businesses, or municipalities on peer-to-peer (P2P) level. A service can be offered or requested at machine level if production capability of one machine is sufficient for the request. As soon as a linking of several workstations is required for a given service request a manufacturing-as-a service offer will be generated. As an additional service to local customers, the configuration of the OMF for new product requests is provided, unless it is not completely automated. The OMF is integrated into the value creation phases of design configuration, production, manufacturing, recycling, repair and disassembly. If no knowledge and skill is available for the condition of operating the OMF, an Open Lab or Fab Lab for training and building the necessary skills is to be selected as an educational location in the local open production network.

CPPS Classification

The OMF is classified as a CPPS entity. Thus, the OMF has physical production capabilities in the form of flexible machine, recycling, assembly, and disassembly stations, as well as data processing and communication interfaces covered in an OMF data platform. The individual OMF stations represent a CPPS entity within the OMF. Through the classification of OMF as a CPPS entity, the OMF itself can be modeled and simulated to analyze its environmental influences. The following high-level architecture model in Fig. 1 shows the designed OMF with its CPPS entities, their network topology and first set of process flows.

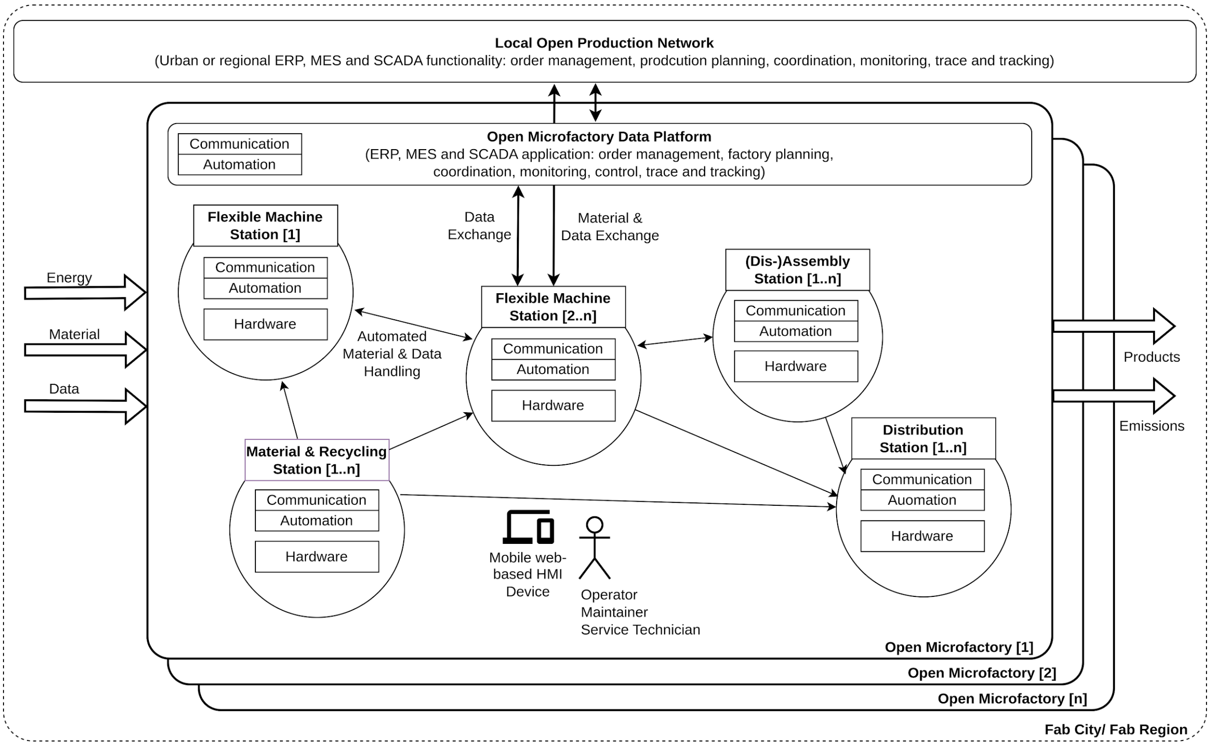

Fig. 1. Representation of a high-level system architecture for Open Microfactory (OMF) within a local open production network.

The individual CPPS entities contained in the OMS are referred to as stations. Each station consists of a Hardware Layer which presents the interface to its physical mechanical, thermal or electrical processes. This layer reflects the physical layer of the CPS concept. The Automation Layer contains the embedded hardware and software components as well as sensors and actuators monitoring and controlling the hardware and its underlying physical processes in real time cycles. This layer reflects the data processing and data storage functions of the CPS concept. The Communication Layer contains an extensive communication interface to realize different protocol standards with different physical transmission methods to exchange product and production related datasets. This layer reflects the communication interface of the CPS concept. Each OMF station or entity exists 1 to n times in the OMF and each OMF exists 1 to n times in the local open production network.

To fulfill the need of end-of-life product handling as well as high integration of automation the OMF provides a first set of defined stations:

The **Material & Recycling Station** describes the material input and storage unit of an OMF with an optional recycling unit to feed-in recyclable material in the production process. This station represents the general material input station of the OMF.

The **Flexible Machine Station** consists of a machine tool unit with a first set of defined technical capability spectrum. The determination of a first set of technical machine functions has been carried out in an expert workshop using the delphi method. Table 1 shows an initial list of the identified technical functions that a machine in the OMF should have.

Tab. 1. Description of identified technical machine features for the Open Micro Factory

Technical machine feature	**Description is the capability of the machine...**
Digitalization	...to be used in a networked process chains with other machines and digital entities in an digital connected and automated environment
Modularity	...to be used in a changing process flow without friction
Processing speed	...to finish machine operations relating a certain manufacturing task as fast as possible
Setup effort	... to be setup for a manufacturing task with minimal effort
Machine hour rate	... to manufacture as efficient as possible per hour
Material diversity	... to process different materials
Technical quality of the process	... to produce products with a given quality
Data compatibility	... to work with different standardized data formats
Technical degree of freedom	... to process materials with a high degree of axial freedom
Service intervals	... to have low service rates
Service life	... to have a high durability and low downtimes
Useable working space	... to have a high workable width, length and height
Investment and operation cost	... to have low initial and operational costs
Technical safety features	... to have integrated safety features to prevent injury

Tab. 1. continued.	
Automation capability	...to work with digital data formats to conduct manufacturing job task in real time control loops
Size	... to be as small as possible
Weight	... to be as light as possible
Energy and Material Efficiency	... to be as clean as possible, regarding vapors, metal powder, CO_2 emission (derived from overall energy consumption), etc.
Noise- and Vibration emission	... to be as silent as possible
Visibility of processes	... to have a visible process
Open-source readiness	... to use open-source hardware and software components.

The feature list shows a large overlap with existing industrial machine features. One significant difference lies in the feature of open-source readiness. In addition to the machine tool unit, a material in- and outfeed block with integrated pre- and post-processing and quality inspection is provided. This station describes the manufacturing of material and components and its processing by a configurable specification.

The **(Dis-)Assembly Station** is used for the assembly of manufactured and purchased sub-components to a functional sub-module or final product. Products and modules that have already been assembled can also be disassembled in this station in order to reuse the contained functional components or to repair components that are no longer functional.

Within the **Distribution Station**, the components manufactured and assembled in the OMF are prepared for the next value-added step outside the OMF. This classically includes packaging and transfer to the next logistic process.

Each station is physically interlinked via *automated material handling systems* through handling robotics and automated guided vehicle (AGV) technologies. Standardized transport interfaces are to be provided for this purpose. The spatial arrangement of the different stations is not considered in the concept since a flexible spatial repositioning of the stations should be given as far as possible within the given space.

Each OMF runs its own local *data platform*. The data platform is used for end-to-end networking of all existing sub-entities. It runs applications or digital services in the domain-fields of order management, resource planning, process monitoring, in general services for efficiently orchestrating all entities as well as trace and tracking of material and energy flows. The network topology is aimed at a maximum distributed structure with P2P communication mechanism through all entities. This P2P capability is also given outside the OMF boundary. This means that one OMF station is able to exchange data with different OMFs or directly with their respective OMF stations. For example, can Flexible Machine Station 1 of OMF 1 exchange data and material with Assembly Station 1 of OMF 3 in the local production network or OMF 2 can exchange data and material with OMF 2. This allows all entities to be virtually connected to each other.

It is targeted to use **OSH factory equipment** and OSS engineering and application tools where it is applicable and possible. In the area of open-source software, the primary goal is to increase ad-hoc configurability to required manufacturing and assembly settings. This is otherwise primarily given by open Application Programmable Interfaces (open APIs) of different computer-aided lifecycle management tools such as computer-aided design (CAD), manufacturing (CAM) or quality (CAQ). A maximum degree of interoperability is necessary for consistent data management and reduced redundancy in data exchange between product design parameters, production planning settings and manufacturing execution platform till machine control level. Using OSS, it is aimed to have optimal continuous integration of new factory and machine configurations. The use of OSH equipment in form of automation components such as embedded systems, sensors, actuators or entire machine units, as described in the concept of open-source machine tools (OSMT) by Omer et al. (2022), gives the OMF maximum autonomy in its strategic and operational decisions. OSH factory equipment provides the local community with expandable service options around the equipment in terms of operation, maintenance, retrofitting or optimization services. The OMF itself represents an OSH entity, similar to the Open Lab concepts where its blueprints, used equipment and configuration settings are openly accessible so that they can be replicated, re-designed and modified in a distributed manner adapted to local requirements.

Open production data

The OMF intends to provide digitally open access to defined production process data which are of particular importance in the context of planetary boundary control parameters. The openly accessible datasets can be used as model and simulation-based optimizations with regard to energy and resource efficiency and thus measure and evaluate decided optimization methods. Through the distributed development of optimized process configurations, adaptation cycles can be reduced. In addition, open data can be used as a transparency tool and include local communities in the decision-making process of new OMF setups like the principle of community monitoring described by Danielsen et al. (2022) which could be adapted to the OMF datasets. Through the open exchange of data between different entities in the entire local value creation network, the decision horizon for supply-chain moves can be expanded and help to increase the overall model sensitivity of the local circular manufacturing model.

04 Conclusion and Outlook

Factories as places of value creation make a significant contribution to prosperity, while at the same time contributing to climate-damaging emissions. Thus, a conversion of these production facilities is of great importance. The OMF functions as an open production entity with minimal spatial and ecological footprint and minimal invasive integration in new or existing infrastructure. It processes a minimal amount of local resources to fulfill the local demand of production with sustainable production patterns and data-in data-out capability as required in the SDG goal 12 and the Fab City concept.

The presented concept of an OMF shows a possibility to implement a circular value creation system with the help of a small-scaled, highly automated, open-source designed factory unit. Thereby, technologies from industrial manufacturing, as well as modeling methods from the field of CPS, Industry 4.0 and Circular Manufacturing are considered. Main features are the integration of highly automated manufacturing sub-stations as well as data management systems, which are based on distributed communication topology to allow P2P data exchange. The concept of open production is taken into account with Open Labs as places of co-creating new circular product design and production methods as well as open-source software and hardware as commons-based equipment units for the OMF to provide maximal autonomy and self-organization.

For the use of data-based methods for the conversion to a circular economy production, the monitoring of process data, especially of environmentally harmful emissions, is necessary. In order not to exceed the limits of defined planetary boundary variables and to be able to make decisions that influence these variables transparently, the concept of OMF describes a disclosure of these process data, according to the principle of community monitoring. This ensures that the direct influences on the environment can be consulted by the community that is directly influenced from the OMF and thus a commons-based organization can be developed around the OMF.

The following discussion points should be listed for consideration in the further development of the OMF concept:

- Which degree of automation is necessary considering that any deployed automation technology requires development, maintenance and refurbishment?

- Which degree of openness regarding open data is necessary and helpful? Can the disclosure of production data add value in terms of material and energy consumption reduction? How can we ensure that there is no blaming of OMF and its operation, but a rational evaluation based on given environmental data?

- How can the OMF be operated in a commons-based mode? How can the described services be developed and designed community-based? How can a transfer of methods developed in Open Labs be transferred and adapted to the OMF?

These questions are to be further illuminated and quantitatively and qualitatively researched.

The OMF concept will be tested in the next step with a concrete set of production capabilities to measure the possibilities of the functionalities described in this concept and their impact and their contribution to the goals of the SDGs, the transition to a circular economy and the compliance with the planetary boundary variables, so that our value creation model can be made regenerative and sustainable.

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