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Distributed Manufacturing: A High-Level Node-Based Concept for Open Source Hardware Production

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Abstract

Distributed manufacturing is presented as a means to enable sustainable production and collaboration. Rather than rely on centralised production, distributed manufacturing promises to improve the flexibility and resilience to meet urgent production demands. New frameworks of production, based on manufacturing models with distributed networks, may provide functional examples to industrial practice. This paper discusses efforts in distributed production in the context of Free/Open source hardware and devises a conceptual framework for future pilots at which open source machines, such as a desktop 3D printer, may be manufactured in a network of open/fab lab nodes.

Keywords

Distributed Manufacturing; Microfactory; Open Source Hardware; Free and Open Source; Circular Economy; Open Production

1. Introduction

The study of distributed manufacturing (DM) has become an interesting topic in literature. Among the milieu of topics in this domain of research, this paper is motivated by two interesting developments: First, manufacturing processes are changing over the years [1–3] and so is the environment in which enterprises, social or commercial, operate. Second, the emergence of the Free/Open Source Hardware (OSH) is noteworthy, as it introduces new forms of collaboration in project development, previously limited to the software realm [4]. A third observation is that both these developments have been made possible by a well-established digital infrastructure we now take for granted. The digital infrastructure has allowed Free/Open Source Software to succeed and, in turn, to inspire the OSH movement [5]. Similarly, digital innovations have enabled manufacturing to move beyond centralised conglomerate systems to new forms of distributed networks of production [6] (that we refer to as DM).

These interesting phenomena are topics of discussion in other papers (see Sec. 1.3) but none fully discuss conceptual frameworks that relate DM and OSH and explore the opportunities they can bring to new models of open production that are not limited to 3D printing of parts. In this paper, we provide a conceptual framework for this relationship, motivated by the needs of future pilots of open production. More specifically, we discuss how DM production units can manufacture open source designs in a network of nodes that simplify the high-level DM abstraction, to benefit OSH manufacturing endeavours. To fully understand the relevance of this opportunity, the rest of this section provides background on DM and OSH (Sec. 1.1) and, a discussion on the main advances in manufacturing and global manufacturing issues (Sec. 1.2).

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1.1 OSH and DM: Overview

Collaboration, open knowledge, and open documentation tools in the form of publicly available projects with permissive or copy-left licenses (Free and Open Source licenses [7]) have transformed the social infrastructure in the software realm [8] and may provide the groundwork to re-shape manufacturing networks in the context of OSH. OSH describes machines, devices, tools, and any physical object whose design specifications are made available to end-users and makers so that such physical objects respect the rights of users and allow for collaboration, reuse, modification, and manufacturing of derivative work [9]. Despite the vagueness of the definition and an ongoing standardisation process [10,11] - OSH, in addition to collaborative and open knowledge benefits, may provide economic advantages [12,13] and flexibility in distributed flows of production.

Innovations in infrastructure and production technology have provided manufacturers, small and large, proximity to end-users in distributed capital and material sourcing production networks. DM refers to the nexus of geographically scattered production facilities that are coordinated for the manufacturing of products. Kerdlap et al. [14] define DM as the production, close to points of consumption, of multiple manufacturing sites, both scalable and localised with reduced transport requirements. In our paper, we consider DM as a system of manufacturing in geographically dispersed components divided into sub-parts with production at different geographical distribution networks in a collaborative setting - similar to Rauch et al. [15] but also encompassing the concepts of open production and bottom-up economics [16]. The distribution network may or may not be coordinated by a single entity or technology, and the governance is from one to many stakeholders.

DM depends on modern infrastructure, information, and communication technologies (ICT), advanced enterprise resource planning (ERP), cyber-physical systems (CPS), and internet of things (IoT) in what is described as Industry 4.0 and smart manufacturing trends to integrate supply chains [17]. DM has also evolved from a value-chain of distributed production across various locations to production networks with small, medium, and large collaborating companies with the challenge to operate with the functionality and capacity of highly refined modern conventional mass production sites [18]. Challenges exist in such complex value-chain relationships [19] and the potential of DM in the context of OSH is to provide means to democratise and decentralise manufacturing practices in a global economy - localised and hyper-customised with international networks of collaboration.

1.2 Advances in manufacturing and sustainability issues

Manufacturing has moved beyond traditional processes [3]. Traditional manufacturing is described as one at a time per need basis production tailored to specific individual needs in a barter system. Production method innovations, over centuries, transformed the scale of production and manufacturing landscape from the industrial revolution to standardisation and high-volume mass production - further refined over the years with machine-dominated robotic automation. Manufacturing today operates in complex labour and capital intensive setting with global distribution networks, high-scale manufacturing, and material intensive needs (see [6] for a historical overview).

Global manufacturing networks are not without fault per se but might be taxing when environmental impact, supply shocks, and local economic self-sufficiency are considered. In the context of environmental impact, global manufacturing modern practices have a responsibility to reduce the environmental burden inflicted by processes in product life cycles [20]. Some of the proposed solutions to the sustainability problem suggest enhancing life cycles [21,22], adopting sustainability programs [23,24], or setting up emission frameworks [25,26]. Supply shocks (e.g., financial [27], pandemics [28,29], commodity shocks [30], natural disasters [31], etc.) also exacerbate the risks in manufacturing flow and environmental impact and may provide opportunities for the consideration of sustainability strategies, such as circular economies [29]. As the effects of environmental impact and disruption of the logistic flow of raw/intermediate materials are exacerbated by supply-chain shocks - there is a significant need for an eco-friendly solution to the manufacturing problem that can be geographically dispersed, localised, and conceivably, more adaptable to shocks.

The need for an eco-friendly solution might be tackled by circular economies. A circular economy is described as a closed-loop flow of resources in the production and processing of goods in an environmentally conscious and ideally waste-free manner (see [32,33] for a more exhaustive definition). In the DM context, it means adding circularity to the distributed flow of resources. As society emerges from production and customisation at a large scale [34,35] to personalised production [36,37], distributed manufacturing in a circular economy setting may be one of the sustainable solutions [38].

1.3 Related work

Previous sub-sections provide background information and serve as groundwork to the definition of the role that DM may play in the production and distribution of open-source projects. Works referred to in this section are inspirations to the contents of this paper; as no equivalent idea of a DM nodes network for OSH is available in current literature.

Among related work in the scope of distributed manufacturing, Wittbrodt et al. [39] explore the life cycles of Open Source 3D printers in a distributed manufacturing setting and highlight how 3D printers may make distributed manufacturing feasible. King et al. [40] follow on the idea and discuss open-source technology to overcome production challenges in communities lacking infrastructure and design desktop 3D printers to provide schools and makerspaces with some manufacturing capability. Similarly, Gwamuri et al. [41] discuss a distributed manufacturing model for self-refraction eyeglasses for developing countries and claim the potential to displace centrally manufactured solutions.

Wittbrodt et al. [42] use the term ultra-distributed manufacturing to describe household-scale 3D printing of complex products. The authors study the case of a solar photovoltaic racking system and show how this mode of production could save costs and improve manufacturing quality. Woern et al. [43] assess distributed manufacturing feasibility in the production of flexible products and find economic and technical advantages in using 3D printers in distributed manufacturing.

Redlich et al. [16] explore theoretical underpinnings of bottom-up economics in the context of open production models in co-creation models of production based on collaboration. A concept drawn onto a microfactory model of open production [44], inspired by microfactory experience in the industry [45] (microfactories may be used or not in DM networks, Sec. 2 will explore further). Ellwein et al. [46] analyse distributed manufacturing and identify customisation, cloud manufacturing, digitalisation, and share-economy as factors that bring analogous co-creation collaborations, termed as the separation of design and manufacturing coupled with new ways of cross-border collaboration in distributed re-location of production.

Literature focuses on the theoretical description of complex paradigms and systems of production or the possibilities of manufacturing in household scales. However, there is work to be done on the definition of a framework that may not only be applied to the production of 3D parts but also, the production of machines.

The motivation of this work is to develop a conceptual framework for future pilots of distributed manufacturing and open production models. Hence, this paper proposes a high-level framework for the problem of how production units in DM networks may organise to manufacture open design projects.

The next section will expand on the industrial and community experience when open-source designs meet distributed production - specifically on microfactories and COVID-19 initiatives in distributed manufacturing. This is followed by the definition and description of how decentralised production of OSH machines could look like as a network of fab/open lab nodes.

2. OSH and DM: industrial and community experience

As OSH design files are ideally freely available on the internet for anyone to download, use, modify and repair. OSH may play a vital role in open design distributed manufacturing in both, the end-product and manufacturing equipment [47].

In the case of OSH as end-products, geographically distributed manufacturing, based on these designs, may save financial, human, and time resources required to design and develop a product from scratch [13]. As manufacturers' development costs go down and the nature of OSH allows for re-use and derivative work of products, different manufacturers may not require to re-design from scratch. Collaborative work encourages standardisation and may increase the availability of components. Ideally, this may allow for the cut down of product redundancy, waste, and planned obsolescence, rampant in today's markets [48].

In the case of open-source manufacturing equipment, the same reasoning follows, with the added advantage that local manufacturers in a localised distributed network may source materials, plentiful in supply from shorter-distance logistic connections. The nature of collaborative design in OSH could also differentiate OSH DM from craft production and allow cost-effective localised manufacturing of products.

OSH is not the only innovation needed to realise DM on a localised scale. Multiple, small high-tech factories may ease the challenge that mass production has with large-centralised sites. Microfactories or desktop factories (see [49] for more information on types) stem from their introduction in Japan in the late 1990s as there was a need to cost-effectively produce small precision components on the micro or mini scale without the reliance on large or inflexible manufacturing sites and machine tools [50]. Microfactories challenge traditional manufacturing aimed at economies of scale, mass production, and capital concentration [51]. Microfactories benefit from locality, flexibility, proximity to other sites or customers, lower carbon footprint, hyper-specialisation, and better access and training of skilled labour [45]. Examples of microfactory production networks include desktop factories at Sankyo production of small mechatronic parts [45], Arrival, an electromobility start-up [52], integration of microfactory processes in electric vehicles production [53], and textile industry manufacturing of smart-clothing accessories [54].

Besides microfactory production in a formal production network - small-scale DM was possible during the COVID-19 pandemic. As hospitals faced acute shortages of personal protective equipment (PPE) [55]; innovative community solutions surfaced in localised, small-scale distributed manufacturing efforts. Face-shield jigs were distributed to local communities by coordinating makers to produce batches of laser cut or 3D printed free and open designs [56]. Besides communities, also start-ups were able to pivot their production. An example in Singapore, a small open-source 3D printer farm start-up was able to quickly adapt and supply face-shields to its local neighbourhood [57]. Several other examples exist [58] and illustrate the ability of small-scale distributed production sites to utilise open designs to adapt their production in real-time to satisfy an urgent supply shortage. Flexibility in production provides resilience in the face of disruptions. Hence, traditional mass production capability may be complemented by utilising local 3D printing capacity for the distributive manufacturing of medical equipment [59]. The same case may apply to other industries as OSH and small-scale DM model of production proliferate in the industry.

3. DM of OSH: A conceptual framework example of machine manufacturing

This section will present a conceptual framework based on a theoretical example of how machines may be manufactured in a DM setting. It is assumed that the source of the machine is freely available and that fab/open labs can join production efforts in a locality or logistic network. To simplify the depiction of such a production network – authors use the example of an existing 3D printer from the Fab City Hamburg project. Background to circular economy initiatives will be provided, in particular, the desktop 3D printer from Fab

City Hamburg. This is followed by an applied conceptual framework to the theoretical node DM production network of such a printer.

Fab City is an initiative that began in 2014 in Barcelona with the premise to transform Barcelona into a circular economy – where by 2054, the city should be able to produce everything the city needs locally [61]. Hamburg became the first German city to pledge to become a fab city [62]. Redlich et al. [44] applied concepts of new patterns of value creation (e.g., networking, collaboration, decentralisation, and bottom-up economics) to describe open labs as distributed open-source microfactories able to set up and replicate manufacturing space and resources to participate in a value creation process that is free of hierarchy and regionally or globally connected. With the rise of the maker scene in the hardware space, fabrication laboratories or fab labs have become a new space for participatory digital manufacturing, whereby local makers, students, entrepreneurs, or anyone may join and make almost anything. Fab labs offer a high degree of creativity and project customisation in a friendly space equipped with minimal tools to assist users and makers in development from design and documentation to prototyping and individualised fabrication [44,60].

Open labs are equipped with machine tools or production technologies whose plans, build instructions, bill of materials (BOM), design files and documentation are freely available. As part of the Fab City Hamburg project, the Open Lab Starter Kit (OLSK) is a project that aims to set up a blueprint of free and open-source machines necessary to establish a digital manufacturing Open Lab [63]. The project originates in the vision to create a distributed network of ‘circular’ production in Hamburg. Local fab labs and open labs are equipped with a range of digital manufacturing machines (Laser Cutters, 3D printers, CNC routers) to provide minimal prototyping or micro-factory capability within the establishments. Machines are designed and developed using distributed control versioning tools (e.g., GIT) and hosted in publicly accessible repositories.

The first machine developed is a desktop 3D printer. The design of the printer is based on an open-source design, adapted to fit local design requirements, and made available in a public repository [64]. The developed 3D printer is planned to be distributed to various makerspaces and institutions throughout Hamburg, with the aim of diffusing digital fabrication technologies throughout the city. The Open Lab Starter Kit project aims to produce and distribute other fabrication machines to labs across the city of Hamburg with in-house developed OSH with easily accessible parts and following the requirements of the Open Source Hardware Association (OSHWA) [65]. The OLSK is a suitable platform to devise a framework on how OSH projects could be produced in a localised distributed way. As a minimal example to answer the question of whether an OSH machine can be produced distributively, the authors consider the case of a simple desktop 3D printer.

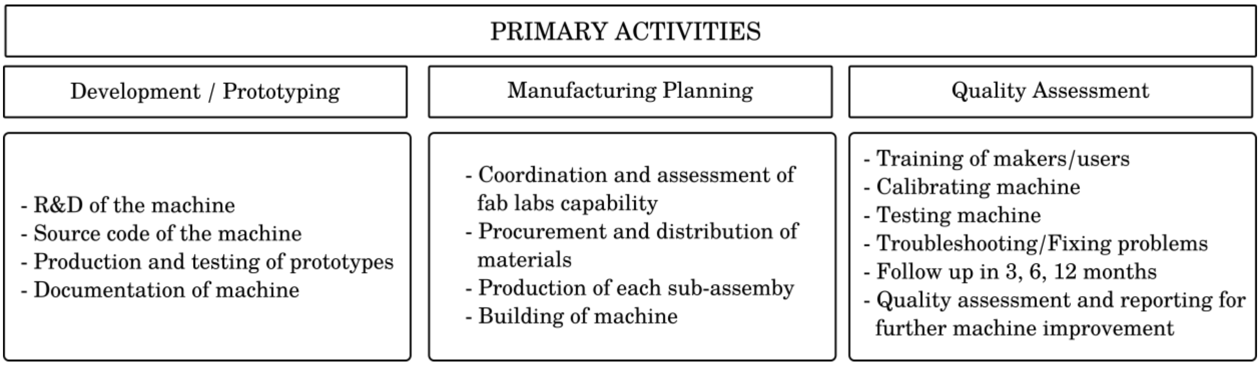
Several components of the OLSK 3D printer are 3D printed and metallic raw materials are locally sourced and machined. For instance, the base of the printer is machinable with a laser cutter, whereas, the rest of the printer requires conventional hand tools. Hence, makerspaces, with the minimal set of digital manufacturing tools, may be able to replicate machines. Table 1 summarises the different sub-assemblies required by the 3D printer.

Table 1: OLSK 3D printer manufacturing process difficulty by sub-assembly

Sub-Assembly	**Manufacturing process**	**Difficulty**
3D printed parts	3D printing	Easy
Frame and structure	Cutting and drilling	Easy

Sub-Assembly	Manufacturing process	Difficulty
Enclosure panels	Laser cutting	Moderate
Electronics and wiring	Soldering and crimping	Moderate/Difficult
Testing	Test station	Moderate
Final assembly	Assembly	Moderate
Software	Flashing firmware	Easy

OLSK 3D printers were built in workshops in Hamburg. It was noted that while manufacturing the 3D printers in our labs, component quality was dependent on the skill set of technicians, troubleshooting ability, the type of machines, features, calibration, and quality of the documentation. In terms of the process from prototyping to manufacturing (see [66] for an overview of production planning topologies), figure 1 summarises the activities that could be equally adaptable to other OSH projects.



PRIMARY ACTIVITIES

Development / Prototyping

- R&D of the machine
- Source code of the machine
- Production and testing of prototypes
- Documentation of machine

Manufacturing Planning

- Coordination and assessment of fab labs capability
- Procurement and distribution of materials
- Production of each sub-assemby
- Building of machine

Quality Assessment

- Training of makers/users
- Calibrating machine
- Testing machine
- Troubleshooting/Fixing problems
- Follow up in 3, 6, 12 months
- Quality assessment and reporting for further machine improvement

Figure 1: Prototyping, manufacturing and quality control activities

As part of a future pilot of DM production utilising the capacity of localised open labs - the DM of machines may use a network of interconnected nodes providing capacity, capability, flexibility, and high

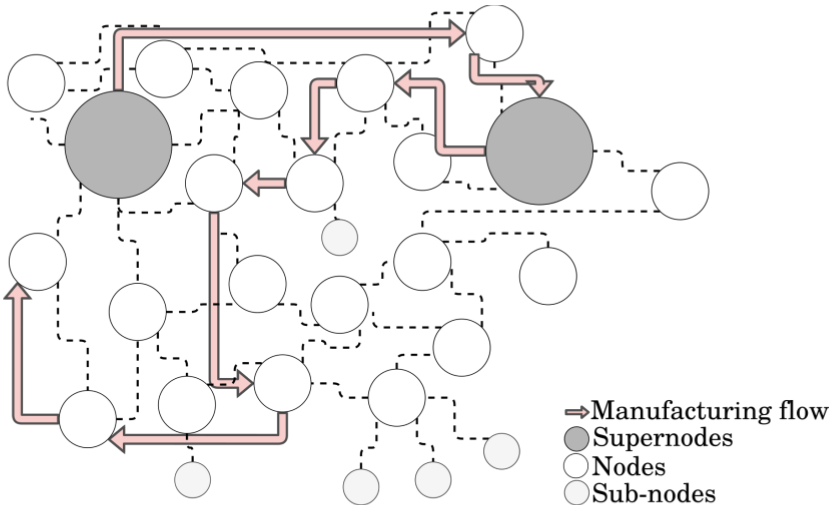


Figure 2: Generalised DM OSH nodes network

customisation/specialisation of manufacturing steps. Figure 2 illustrates the concepts how OLSK machines could be manufactured locally by utilising existing microfactory capability within fab/open labs in the city.

We consider a node as a microfactory in the form of a fab or open lab, able to produce, test, and manufacture a part, component, or sub-assembly of the machine. Nodes are distributed across a city and can undertake one or more work packages as required. The work across nodes might be distributed according to the product to maximise efficiency, minimise logistic travel and reduce waste.

A node is a simple representation of a microfactory that encompasses and simplifies other external factors, inherent to the running of such a micro-production unit (e.g., employees, marketing/business plans, monetary flows). Hence, a node does not address such issues, but it represents on a higher level, no matter the internal configuration or running of it, a microfactory able to produce, test, and manufacture parts assigned to it.

Nodes in the DM OSH production network may act as manufacturers of new nodes if they have the capability of such. Nodes may collaborate in the production, assembly, and flow of materials, parts, sub-assemblies, and products. A system with small-scale production is flexible and resilient against supply-shock production flows. The manufacturing of one machine, for example, may be divided between nodes in the network so that each node produces a part or sub-assembly according to the capabilities and capacity requirements. A node may become a sub-node, which are nodes capable of taking over the production task of another node. Nodes may or may not be part of the DM network of a specific machine. This means that nodes networks may participate in the production of more than one machine and may not be restricted to the production flow of one manufacturing project. Similarly, there may be nodes capable of producing all the manufacturing steps for the machine at once, these are super-nodes and may or may not participate in one or more sub-assemblies of a machine.

The flow of materials and parts may be traceable and trackable through digital product passports. Digital product passports may provide an intelligent, verifiable way to support such relationships (this is depicted by the traced lines connecting the nodes). However, challenges in this field remain. There are stakeholder policy issues [67], requirement composition challenges from an enterprise perspective [68], digital product passport policy guidance such as the upcoming EU Battery Regulation [69], implementation initiatives such as in Hamburg [70], Prague [71], Glasgow [72] or Brussels [72] (for an exhaustive list see the EU Joint Research Centre (JRC) [73]).

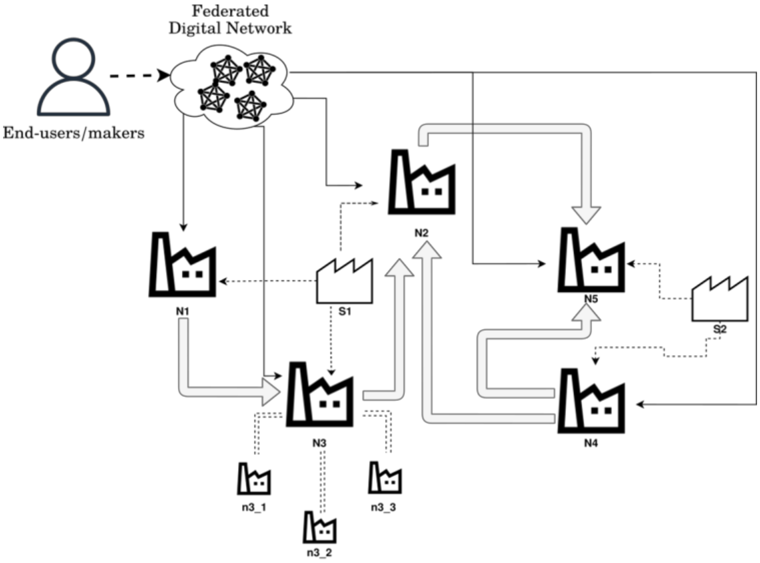


Figure 3: OLSK DM network representation

Such a complex network of nodes may also require high optimisation capability to be able to assess the most optimal way to plan production, a topic of current research, and with work in progress algorithms [74] [75].

A simplified representation of how such a network of nodes may be applied in a pilot is illustrated in Figure 3, where:

- *N1*: Frame and structure producing node
- *N2*: Enclosure panels and pre-assembly node
- *N3*: 3D printing node
- *n3_1*, *n3_2*, *n3_3*: 3D printing sub-nodes
- *N4*: Electronics and wiring node
- *N5*: Final assembly, electronic testing, and software flashing node
- *S1*, *S2*: Local part suppliers

Nodes *N1*, *N2*, *N3*, *N4,* and *N5* exchange information by using the digital infrastructure and produce each sub-assembly or step independently of each other. Production may flow linearly 1-1 as illustrated from *N1* to *N3* or with multiple inter-dependencies as in *N4* to *N2* and *N5*. As expected, the system provides some resilience as sub-nodes *n3_1*, *n3_2*, *n3_3* may backup *N3* if required. As the network grows, more sub-nodes may replace other microfactory nodes.

The cloud in Figure 3 represents a federated digital network, a network infrastructure that is distributed and decentralised across instances of a service, in this case, a DM network. The role of the federated network is to provide the tools to track and trace production flow, decentralise, encourage open participation, and provide means of good exchange supporting both, barter and traditional accounting-based systems (see [76] for more details on resource, event, and agent models). This may provide means of recycling, re-use, and minimising waste in a circular economy model. Additionally, the digital network may be complemented by web3.0 technology: blockchain, decentralised autonomous organisations, decentralised finance, self-sovereignty, and privacy tools [77]. However, as technology evolves, it is unclear how such a system and governance may look in practice on a regional level.

Distribution networks, logistics, e-commerce platforms, and stakeholder relationships, due to simplicity of exposition, are not included in Figure 3 but the manufacturing flows may theoretically be adaptable to changes in such factors. Similarly, nodes with non-manufacturing tasks may also be included in the future (i.e., small-scale specialised transportation distribution nodes or federated instances of e-commerce nodes). As with regards to suppliers and proximity mapping for larger-scale production networks, models such as know-how proximity data matrices [78] may be suitable for waste reduction and sustainability applications. However, further research in this field, in the context of DM, is needed.

DM of OSH may assume the node configuration described in this section. Node networks may grow separately from each other in different regions or grow organically in one region towards other regions. The distributed nature of this system allows future communication between geographically distant networks of nodes. Hence, any fab or open lab in such a network can participate in the manufacturing process. As networks of nodes expand, they are not confined to limited regions of production and may communicate cross-regionally or globally with each other if required. The node configuration provides a high-level proposition on how regions may organise their fab/open labs in a democratised and open production flow. Democratised as producers may have access to such network of production. Open production as nodes may participate in the manufacturing of any OSH part, sub-assembly, or project they may be capable to produce.

As DM enables democratisation [79] and the industry continues to innovate global production networks and value creation - OSH may play a vital role. Open source machines, like the OLSK, in the mesh of fab/open labs, are a starting ground for future endeavours in building distributed manufacturing networks. In the future, local/regional value creation systems may have the ability to become circular economies, self-governing, self-reliant, and resilient to supply shocks. Fab City movement may foresee this trend emerging at the city level, but the nature of open distributed networks is not limited to hard-bound perimeters, it is global.

The suggestions in this paper support effort in localising production in a distributed manner and encourages research-led endeavours to explore alternative production networks that aim to be open, sustainable, and adaptable. The authors propose a node-organisation framework of fab/open labs able to manufacture a desktop 3D printer and likewise, other machines by that same approach. The extent to which such possibilities might or might not apply in practice is thought-provoking, particularly, when compared to existing manufacturing literature and current capacity/capabilities in the global economy. Further work is needed in the form of pilots and case studies to evaluate to what extent is distributed manufacturing of open source hardware ready to undertake such an open production endeavour.

4. Further research

Localised distributed manufacturing in open production spaces is referred to as a new category of production [6]. Distributed manufacturing models in open production spaces lack production planning models [80] and there is a need for research on open distributed production algorithms. Hence, future research may expand on how the conceptual framework, presented in this paper, will organise each of the production node's scheduling, capacity allocation, and logistic provisioning.

The distributed manufacturing of open-source machines, such as our desktop 3D printer, utilising the machine capacities of the geographically distributed makerspaces within a city would also serve as an ideal pilot project to test and evaluate production strategies for optimum utilisation of the production capability of networked open production spaces.

Production allocation and fab/open labs manufacturing specialisations may be of interest for future research too. For instance, is it sensible to divide a manufacturing task into sub-assemblies and distribute sub-assembly production to different microfactory nodes? Or is it more sensible to allow each microfactory to become a super-node and produce one machine each? Furthermore, questions remain about the role of ICT implementations of inter-connected systems making use of web3.0 and Industry 4.0 technologies. Similarly, the role of policymakers and green agendas. There will be trade-offs between manufacturing capacity, efficiency, capability, and sustainability. All these issues add to the role of OSH licensing and certifications, which may be a major setback to real-life implementations of such policies and projects.

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