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Tracing sustainable production from a degrowth and localisation perspective: A case of 3D printers

Christina Priavolou

Ragnar Nurkse Department of Innovation and Governance, Tallinn University of Technology (TalTech), Akadeemia Tee 3, 12618, Tallinn, Estonia

Katerina Troullaki

Bioeconomy and Biosystems Economics Lab, Department of Environmental Engineering

Technical University of Crete, Akrotiri Campus, 73100, Chania, Greece.

Nikiforos Tsiouris

Ragnar Nurkse Department of Innovation and Governance, Tallinn University of Technology (TalTech), Akadeemia Tee 3, 12618, Tallinn, Estonia

Chris Giotitsas

Ragnar Nurkse Department of Innovation and Governance, Tallinn University of Technology (TalTech), Akadeemia Tee 3, 12618, Tallinn, Estonia

Vasilis Kostakis

Ragnar Nurkse Department of Innovation and Governance

Tallinn University of Technology (TalTech), Akadeemia tee 3, 12618, Tallinn, Estonia.

Berkman Klein Center for Internet & Society

Harvard University, 23 Everett Street, Cambridge, MA 02138, USA.

Abstract: An emerging commons-oriented mode of production that combines globally accessible knowledge with distributed manufacturing has recently been presented as a better fit for sustainable degrowth and localisation, compared to incumbent practices. To tentatively test this potential we select the case of 3D printers. The production of 3D printers varies within a spectrum from proprietary and industrially produced to open-source and locally manufactured. We compare different 3D printers within this spectrum, adopting a values-based life cycle analysis tool that allows for a critical evaluation of the sustainability of 3D printers from a degrowth perspective. An emphasis on the prospects for sustainable localisation is given at each life cycle stage. We find significant advantages of open-source 3D printers in terms of education, experimentation and maintenance, and enhanced conviviality in case parts of their manufacturing is localised. Still, to a large extent their manufacturing process remains a highly centralised process, hindering additional benefits, and coherence with sustainable degrowth and localisation. We conclude with insights on how openness in terms of materials production and proper documentation of the manufacturing process, as well as a multi-level organisation for local production could lead to more sustainable practices.

Keywords: 3D printers; sustainable production; degrowth; localisation; life cycle thinking; open source

1. Introduction

The rapidly escalating climate crisis and the recent supply chain disruptions caused by the COVID-19 pandemic and the Russo-Ukrainian war are shaking the foundations of the incumbent economic system. Critiques regarding the unsustainability of modern economies centre around their increasing production and consumption throughput, as well as their reliance on global supply chains (Feola, 2020; Foster et al., 2010).

Rethinking conventional production and consumption systems is urgent and the challenge has been taken on by various streams of thought proposing alternative systems of production (and in some cases consumption), including the circular economy, bioeconomy, and degrowth. While the first two are not directly critical to capitalism and economic growth, degrowth proponents argue that economic growth cannot be sufficiently decoupled from environmental impacts, which renders further growth of the economy unsustainable (Sekulova et al., 2013; Van den Bergh and Kallis, 2014). According to the latest IPCC (2022) report, degrowth is considered the major alternative pathway for system transformation to that of 'green growth'. The question is then how degrowth can become environmentally and socially sustainable, rather than being "a catastrophic descent" (Kallis, 2011); and what production mode could be compatible with such an imperative.

At the same time, consecutive crises of recent years have culminated in a pressing call to address the vulnerability of production systems to supply chain disruptions. The relocalisation of production has been proposed as an alternative in this respect being a focal point in the degrowth literature (Hankammer and Kleer, 2018; Hankammer et al., 2021; Lizarralde and Tyl, 2018; Tsagkari et al., 2021). Relocalisation in the production of technologies pertains to all the life cycle stages of a technology, ranging from the use of local resources to local manufacturing and recycling processes (Shuman, 2013). In addition, it includes the recruitment of local workforce and the use of local low-tech ideas to support distributed manufacturing and maintenance (Kostakis et al., 2018; Tsagkari et al., 2021). The result is usually increased resilience, autonomy, efficiency in use of materials and energy, and reduction of logistics involved in relevant processes (Lizarralde and Tyl, 2018; Shuman, 2013; Tsagkari et al., 2021).

Kostakis et al. (2018) have explored emerging commons-based production practices brought together under the umbrella of the Design Global - Manufacture Local (DGML) configuration. In DGML processes, technology design is developed as a global digital commons (Benkler, 2006), while production takes place locally, often using shared infrastructures, such as in makerspaces and fab labs (Kallis et al., 2018). Kostakis et al. (2018) argue that particular characteristics of DGML production, i.e. sharing, on-demand production, and design-embedded sustainability, are compatible with the sustainable degrowth imperative.

In this article, we aim to empirically assess the compatibility of DGML production with sustainable degrowth and localisation compared to traditional production processes. We focus on a technological artefact that has been presented as an exemplar of DGML production, i.e. 3D printers (Kostakis et al., 2018; Pazaitis et al., 2021). Similarly, several degrowth scholars and localisation enthusiasts (Kerschner et al., 2018; Molitch-Hou, 2020) have argued for the potential of 3D printers to reduce the environmental impact of the contemporary industrial world, fostering decentralised manufacturing processes and local supply chains.

However, current studies do not consider the way that a 3D printer is produced as a parameter of analysis. Positing that openness and potential for localised manufacturing - i.e. the structural elements of the DGML configuration - are key features embedded in the life cycle sustainability of technologies (Vetter, 2018; Lizarralde and Tyl, 2018; Ralph, 2021), we investigate a spectrum of 3D printer models ranging from proprietary and industrially produced to open-source and locally manufactured ones. We critically discuss distinctions between proprietary 3D printers and open-source ones, considering their life cycles through a values-based lens and focusing on localisation as a critical concept that promotes sustainability in technology production (Olivier et al., 2018; Ralph, 2021).

In summary, the study aims to assess the compatibility of the whole 3D printers' lifecycle with sustainable degrowth and localisation, and understand whether the DGML production configuration enhances this compatibility. We operationalise the imperatives of sustainable degrowth and localisation by employing a values-based sustainability assessment approach, as explained below. From a higher-level perspective, we illuminate understudied aspects of DGML, moving from a commonly proposed potential for sustainability towards its empirical understanding.

The article is structured as follows: Section 2 introduces the theoretical framework of this article, presenting a commons-based configuration towards sustainable degrowth and localisation. Section 3 describes the methodological approach of the research process, which follows a values-based life cycle approach to sustainability assessment. Section 4 presents the research outcomes discussing how openness and localised production may contribute to sustainable degrowth and localisation, and the barriers to this end. Finally, section 5 summarises the main findings and points to proposals for future research and action.

2. Exploring pathways for sustainable degrowth and localisation in production

2.1. Degrowth and localisation: A critical discussion

Growth, as in the increase of the Gross Domestic Product (GDP), is an imperative of the current economic system which has detrimental ecological and social consequences (D’Alisa et al., 2014; Demaria et al., 2019). One of the concepts aiming to reverse these consequences is degrowth. Degrowth is a normative concept, much like growth and development economics, aiming to reduce the overall resource and energy throughput. Throughput is the result of the extraction, processing, logistics (transportation and distribution), consumption and, finally, disposal of materials and energy required for these procedures (Kallis, 2011). Degrowth aims to transition onto an alternative political and economic paradigm with a vastly smaller resource throughput whilst being socially and ecologically sustainable (Kallis et al., 2018; D' Alisa et al., 2014). Degrowth scholars have proposed diverse socio-technical trajectories towards this transition, but all converging towards limiting the resource throughput and redirecting technological change to increase resource efficiency rather than labour productivity (Kallis et al., 2018; Demaria et al., 2019).

Degrowth's reliance on technological change has led to complex debates (Kallis et al., 2018; Kerschner et al., 2018). Indeed, technology pervades all human -and non-human- activities and shapes, or even dictates, our way of life and the environment around us (Feenberg, 2002; Giotitsas, 2019). Jaques Ellul (1964), exploring the relations between technology and degrowth, went as far as stating that our technological system has led to a growth-oriented economy rather than the other way around. According to Ellul and leading degrowth thinker, Ivan Illich, economic growth transforms tools from means to ends with Illich (1973) claiming that technologies should be re-designable, repairable, modular, and even re-conceptualised by their users. The technologies that tend to lean towards sufficiency and creativity; adopt the open-source 'philosophy'; are designed for affordability and durability; explore tacit knowledge; empower communities through access to means of production; and promote localisation of production and logistics; are defined as convivial (Kerschner et al., 2018; Ralph, 2021).

The latter element of convivial technologies, localisation, may arguably present the most radical shift for production systems under degrowth. Especially considering the global spatialities of incumbent technologically mediated systems (Mocca, 2020). Localisation is the move away from globalised markets and supply chains, with the two not being mutually exclusive (Ajulo et al., 2020). Localisation of production is seen by many degrowth scholars as a key element that can foster the social and ecologically sustainable transition that degrowth proposes (Kallis, 2011; Gibson-Graham, 1996). Through localising production, communities could become more self-sufficient, autonomous and develop local economies (Ajulo et al., 2020).

However, if degrowth is to contribute to the aforementioned socially and ecologically sustainable transition, it should not focus solely on localisation and consider wider geographical spatialities and relevant infrastructures. Only a handful of studies tackle this spatial perspective (Demaria et al., 2019; Krähmer, 2022; Olsen et al., 2018). Since technology reflects the socio-economic system and its power relations (Bijker et al., 1987; Feenberg, 2002), then a framework of convivial technology may create different spatial dynamics. In other words, technology that embodies the values promoted by degrowth such as equity, inclusiveness, and sustainability may accommodate the conditions to move past the duality of global-local. We posit that the DGML configuration, which were further discuss in the following subsection, may offer the necessary tools for cross-spatial forms of organising and producing.

2.2. Design Global - Manufacture Local: A sustainable production configuration?

In the search for sustainable production and organisation processes under the degrowth agenda, the commons have been brought forth as communal practices to manage a certain resource (Bollier, 2014; Kostakis, et al., 2015). Radical commons-oriented configurations for organising, producing, and consuming have been introduced in the past few decades, following the information and communication technologies, with an eye to sustainability and human welfare (Benkler, 2006). Such modes are viewed as an umbrella political economy for exploring alternative sustainable practices (Kostakis et al., 2015), enhancing distributed manufacturing processes via local manufacturing technologies.

One such configuration, codified as "design global, manufacture local" (DGML), has been proposed, building on the distributed production of technologies within the commons framework (Giotitsas et al., 2020; Kostakis et al., 2016). It has been observed that commons-based communities appropriate technology to create positive feedback loops for degrowth and localised manufacturing and maintenance (Kostakis et al., 2015, 2016) as manifested in numerous fields, including agriculture, building construction, and energy systems (Giotitsas et al., 2022; Priavolou et al., 2021; Troullaki et al., 2022).

More specifically, the DGML configuration embraces three interlocked elements: the non-profit-motivated design of technologies, the local manufacturing aspect of the DGML configuration, and the mutualisation of resources, such as information and tools (Kostakis et al., 2015). In that regard, DGML technologies are designed for longevity, while ecological sustainability may be fostered through the design-embedded sustainability of technologies and their potential for on-demand production (Kostakis et al., 2016). Resources are shared in the form of online information as a global digital commons, while solutions are manufactured locally in physical infrastructures (e.g., machines, tools). Digital commons are characterised by the variably defined element of openness (Nafus, 2012; West, 2003). Openness may pertain to a lack of prohibitive access licences. Or to the inclusive and collective development of a technology, strengthening the relationship dynamics within the involved community (Priavolou and Niaros, 2019; Shaikh and Vaast, 2016).

Further, the DGML configuration considers features, such as global cooperation as well as adaptability amongst local actors, including governance and biophysical conditions, to achieve decentralised production at the local scale (Ralph, 2021). It introduces more inclusive forms of production and consumption (Kostakis et al., 2016), while reducing the need for transporting materials and products through localised processes. Nevertheless, claims about its sustainability potential still rest on thin empirical foundations (Kohtala, 2015). This article is a tentative empirical exploration towards this direction focusing on 3D printers.

2.3. 3D printers as benchmarks for degrowth and localisation

In recent years, localised production processes are increasingly facilitated by technologies that have been associated with lower energy throughput, user autonomy, and inclusivity like laser cutters, milling machines, and, more prominently, 3D printers (Moilanen and Vadén, 2013; Srai et al., 2016; Windt, 2014). 3D printers specifically are additive fabrication machines that create a physical object from a digital design and have been highlighted in the booming field of sustainability transitions as potential tools for revolutionising production (Köhler et al., 2019; Kohtala, 2015; Lipson and Kurman, 2013; Maric et al., 2016).

3D printers have been discussed for their potential to reduce logistics, material waste, and overproduction, as well as to increase product lifespan and enable on-demand production (Khosravani and Reinicke, 2020; Molitch-Hou, 2020). Especially in light of the COVID-19 pandemic, 3D printing has emerged as a novel approach for communities to rapidly respond to disasters and crises, satisfying global and local needs (Dartnell and Kish, 2021; Newman, 2020; Tönissen and Schlicher, 2021). Further, 3D printing facilitates recycling processes for certain materials, such as lithium batteries and metal components (Berger, 2019; Giurco et al., 2014), hence promoting end-of-life systems and supporting localisation (Ralph, 2021). In that sense, 3D printers have been touted as paradigmatic cases with the potential to transform production in society, triggering discussions around ubiquitous and autonomous manufacturing (Birtchnell and Urry, 2013; Dubey et al., 2017; Gershenfeld, 2005).

After the core Fused Deposition Modeling (FDM) patent expired in 2009, 3D printing innovation has bloomed both in proprietary contexts and within the open-source movement (Laplume et al., 2016). For instance, 3D printers can be produced by manufacturing companies following the conventional production model, keeping the designs, firmware, and software of the machine closed and thus preventing users from intervening in relevant processes. At the same time, open-source communities develop low-cost 3D printers based on DGML principles. They openly share information and innovations, allowing continuous improvements in the design, firmware, and manufacturing of 3D printers. Or, at the very least, the replication of a 3D printer is not prohibited or requires licensing. The development of the RepRap project, the first open-source 3D printer whose production may approximate the DGML configuration, has further boosted the propagation of 3D printing technology as many built on its rudimentary design (Jones et al., 2011).

With regards to sustainability assessments around 3D printing technology, ecological, social, economic, and integrated assessments have been conducted as provided in Table A1 (Appendix A). Most empirical studies have compared the process of 3D printing with industrial production processes (Cerdas et al., 2017; Gebler et al., 2014; Petersen and Pearce, 2017). Also, different 3D printing technologies (Faludi et al., 2015; Kellens et al., 2017) or alternative additive and subtractive manufacturing techniques (Doran et al., 2016; Foteinopoulos et al., 2019) have been assessed. Further, Life Cycle Assessment (LCA) has been widely applied to estimate the ecological impacts of 3D printed products throughout their life cycles (Li et al., 2017; Ma et al., 2018; Yao and Huang, 2019; Munoz et al., 2021). Potential risks of 3D printing technology related to the creation of rebound effects and waste of material and energy resources have also been identified (Giurco et al., 2014).

In such empirical studies, the focus of analysis are the 3D printed products rather than the printers themselves. The whole life cycle of the 3D printers has rarely been considered with studies usually employing impacts-based approaches to sustainability assessment, which is vague in terms of how sustainability is conceptualised. They implicitly adopt efficiency-oriented criteria, ignoring secondary effects of the hegemonic efficiency strategy (Figge et al., 2014). The insufficiency of such efficiency-oriented methods has been stressed by degrowth scholars (Schröder et al., 2019).

In this article, we bring 3D printers themselves into focus. We hypothesise that 3D printers produced in a DGML way would be more compatible with sustainable localisation and degrowth throughout their life cycles. We aim to tentatively test this assumption, by exploring community projects that develop, tinker with, and use differently produced 3D printers, as explained in the next section.

3. Research approach

3.1. A values-based approach to sustainability assessment

Sustainability assessment approaches usually employ impacts-based methods focusing on the thematic areas of environment, society, and economy. Although thematic conceptualisations of sustainability facilitate the assignment of indicators to measure sustainability, i.e. the operationalisation of sustainability, the values guiding the selection of indicators are rarely transparent. This may obscure the fact that sustainability is a value-laden concept that reflects the rationality of the decision-makers.

Currently, the most established methods for assessing sustainability adopt the life cycle principle. Particularly LCA translates all material and energy inputs and environmental releases throughout a product's life cycle to potential environmental impacts; lacking, however, a values-based lens (Troullaki et al., 2021). For example, the fact that LCA is an eco-efficiency tool is rarely mentioned in research applying it. Alrøe et al. (2017) associated values-based approaches with Weber's value rationality and non-consequentialist ethics, illuminating how things are done rather than the outcomes. Further, Dahl (2012) stressed the need to apply values-based approaches to integrate ethical principles in sustainability transitions.

Such an approach is the Matrix of Convivial Technologies (MCT) (Vetter, 2018), which was designed based on values prioritised by degrowth-oriented communities (Robra et al., 2020). The MCT is a self-assessment tool intended to be used by communities for making their technologies more 'convivial' as introduced by Illich. Paraphrasing Illich (1973), conviviality is the proper level and kind of development for satisfying the needs of human societies. As such, it can be seen as a broader vision for sustainability agnostic to the growth imperative (Ralph, 2021). A more etymological definition of conviviality could be "the art of living together" (con+vivere). Hence, convivial technologies are perceived as technologies designed to 'live together' with other human and non-human elements in their immediate social-ecological environments. In this case, conviviality is linked to localisation, autonomy from industrialisation, affordability, and access to knowledge required to produce and maintain technologies (Kerschner et al., 2018; Lizarralde and Tyl, 2018).

The MCT adopts a transparent values-based approach rather than fragmentation in environmental, social, and economic impacts; still covering all of these impact areas in an integrated way. For instance, assessing whether the production of a technological artefact creates the ‘Need for foreign experts’ or rather ‘Uses local knowledge’ is a criterion touching simultaneously upon economic, political, cultural, and ecological aspects. We here employed the MCT as a comprehensive normative schema to assess degrowth-inspired sustainability aspects of 3D printers throughout their life cycles.

The MCT is a two-dimensional matrix that includes the life cycle levels of a technological solution across the one dimension (i.e., materials, manufacture, use, and infrastructure) and correlates them with the five values across the other dimension. In the MCT, the values used to operationalise conviviality are:

i) Relatedness, i.e. how technology affects the relations of people with nature, with other people and with technology itself,

ii) Access, i.e. who can produce, use, and dispose the technology, where, and how,

iii) Adaptability, i.e. how independent or linkable a technology is to its environment,

iv) Bio-interaction, i.e. how a technology interacts with the ecosystem, and

v) Appropriateness, i.e. what is the relation between the inputs and outputs of the technology considering a given context.

In practice, to assess technologies against these values, the matrix comprises pairs of antagonistic terms that specify and enrich the meaning of each value. Following Vetter’s proposition for a context-sensitive use of the MCT, we adjusted the original version of the matrix to suit the technology and context under study (Appendix D). Certain antagonistic terms were omitted and others rephrased so as to keep the matrix simple and comprehensible by 3D printers practitioners.

With regards to the MCT’s infrastructure level, we defined it as the infrastructure closely connected with and required for the efficient use of the 3D printer (e.g. computer, electricity, software). However, during the early applications of the matrix we observed considerable overlap of the infrastructure level with issues addressed in the use level, which created much confusion without adding insights. Therefore, we omitted the infrastructure level and integrated certain antagonistic terms of it into the use level. Indicatively, we considered the electricity consumption aspect, which is non-negligible during the operation of 3D printers, in the appropriateness dimension of the use level. Hence, our analysis spanned across three life-cycle levels of the 3D printer: i. materials, which includes harvesting, processing, and disposal of materials, ii. manufacturing, which pertains to manufacturing 3D printer preproducts and assembling them, and iii. use, which includes the operation and maintenance of 3D printers. Our methodological steps are thoroughly presented in the next session.

3.2. Methodological steps

Aiming to explore whether DGML-based 3D printers are more compatible with sustainable degrowth and localisation than industrially produced ones, we brought the production process of 3D printers into the foreground. We examined 3D printers that differ in how they are produced, allowing for different levels of openness and localised manufacturing. To allow for a tentative comparative assessment, we focused on desktop 3D printers, and particularly the Fused Filament Fabrication (FFF) technology, one the most widely used and commercialised 3D printing applications (Pazaitis et al., 2021).

We began with a literature review of sustainability assessments around the 3D printing technology (Appendix A). We then launched a preliminary round of 12 interviews to allow for a tentative understanding of the current situation at an EU level. Through snowballing, we reached out to individuals and makerspaces to better comprehend and record their experience regarding the use of 3D printers. The interviewees were do-it-yourself enthusiasts, as well as individuals from maker communities, and 3D printing enterprises. Our inquiry focused on the manufacturing process of 3D printers, the context and purpose of use, the maintenance process, and the open-source aspects of 3D printers, as presented in Table B1 (Appendix B). Based on the interviewees' feedback, we also recorded a set of 3D printer models with comparable performance and capabilities as indicated in Table C1 (Appendix C).

Subsequently, considering country-level differences in terms of technology production and supply chain management (Furman et al., 2002; Vachon and Mao, 2008) but also for proximity reasons, we narrowed our studied context to Greece. We presumed this could allow a more concise and focused assessment of 3D printers with the MCT. Intending to explore emerging alternative forms of manufacturing, different to incumbent practices, and informed by the preliminary work, we focused our inquiry on communal initiatives like fab labs and makerspaces. Such places are incubators for the rising maker culture (Kostakis et al., 2015; Maxigas, 2012). Although makers have usually limited agency in the initial stages of the supply chain (e.g. extraction and processing of raw materials), they engage in a large part of the manufacturing process.

We thus conducted semi-structured interviews with six makerspaces and fab labs that engage in a wide range of activities as shown in Table E1 (Appendix E), using the MCT as a guide. Two to three community members of each makerspace or fab lab participated in each of these interviews. We documented the experience of these organisations with 3D printer models that are comparable based on our analysis during the first round. Additional communications took place to complement the analysis and provide clarifications when necessary.

The six organisations operate within the Greek context, with varying interests and fields of expertise. Organisation A is a fabrication and research laboratory and official reseller and service centre for MakerBot in Greece, whose members use 3D printers for education, experimentation, and prototyping. They also sell 3D printers and provide maintenance services to their customers. Organisation B is a digital innovation hub that uses 3D printers for prototyping and education purposes, while occasionally building spare parts for customers. Organisation C is a research collective that uses 3D printers for experimentation and education without engaging in commercial activities. Organisation D is a makerspace that focuses on experimentation and the development of innovative prototypes, using 3D printers for their own use and selling. Organisation E is a makerspace that provides services in different stages of prototyping and final manufacturing, while procuring spare parts from local technicians (like Organisation F) or abroad when necessary.

Organisation F is an exceptional case for the Greek context given that, to our knowledge, it represents the only case in Greece (other than individual hobbyists) where a 3D printer was partially produced following the DGML configuration. It is the first open-source 3D printing company in Greece that builds and sells customisable Prusa i3 (successful model of the RepRap project) variants on demand. All their printers are based on open designs, which in many cases have been modified and published again openly. When they started operating in 2008, the economic crisis in Greece favoured their activities, as the market from abroad was basically closed. They used to invite customers to participate in hands-on workshops where they manufactured their 3D printers themselves for a small additional fee. However, once purchasing low-cost 3D printers from China became possible again, they had to transform their business model. Their main activities today are manufacturing 3D printers locally for education and own use, designing and making 3D printed products and offering technical services to end-users.

In an attempt to distinguish different production models between the studied 3D printers, we identified certain elements both for the design and manufacturing processes of 3D printers. As explained below, two of these elements refer to the design process and two to the manufacturing process of 3D printers. All these production elements emerged from literature data and were complemented by discussions during the first round of interviews.

Regarding the design process, we considered the trichotomy of transparency, accessibility, and replicability which are the most cited elements of openness in literature (Balka et al. 2010, 2014). These refer to the freedom to study the design files of a technology and to participate in its development and its assembly process, including the bill of materials and fabrication instructions. Another important element of openness is the commercial usability of a technology that describes the freedom to distribute information (Bonvoisin and Mies, 2018). To account for these openness elements, we included the licence type and documentation as two basic elements to distinguish different openness levels in the production of 3D printers. In addition, elements associated with the documentation processes (i.e. CAD files, assembly instructions, and bill of materials) were pointed out in our preliminary inquiry as significantly important when it comes to the local manufacturing of 3D printers.

Moving from the design to the manufacturing process of 3D printers, the decomposition of a technology into modular components proved to be a critical element that enables the localised manufacturing of technologies (Kostakis, 2019). In the case of 3D printers, a kit version of a 3D printer, including a set of motors, gears, axes, bolts, and other hardware equipment together with detailed instructions for assembling the components together, offers this opportunity. In addition, an essential element that lies beyond the control of the original manufacturing company, is the local capacity for manufacturing, which pertains to the local availability of various resources (Kostakis, 2018; Fiszbein, 1997), like infrastructural (i.e. buildings, equipment, tools), human (i.e. skills, expertise), natural (i.e. raw materials and energy), and organisational ones (e.g. supplier and manufacturing organisations, training centres). These dimensions emerged in our case from literature data, while some of them were also reported during the first round of interviews as possible factors that may affect the potential for localised manufacturing of 3D printers.

Consequently, we identified four elements that differentiate the production process of 3D printers and, if present, approach the DGML production paradigm. These are:

i) the type of licence, which defines the restrictions under which one is allowed to access, re-use, modify, and redistribute the design,

ii) the availability of open documentation, which refers to the publication of all design files and instructions (CAD files, board schematics, firmware files, assembly instructions, and bill of materials) needed to replicate the original 3D printer,

iii) the availability of a kit option, which enables the local assembly of 3D printers' components, and

iv) the capacity for local manufacturing, i.e. the local availability of infrastructural, human, natural, and organisational resources required for decentralising the manufacturing process.

In Table 1, our studied 3D printer cases are marked in terms of satisfying or not the four production elements.

Table 1. Production elements against studied 3D printer cases (model | organisation)

<table>
<tr><th rowspan="3">Model | User</th><th colspan="4">Production elements associated with DGML</th></tr>
<tr><th colspan="2">Openness (design)</th><th colspan="2">Localisation (manufacturing)</th></tr>
<tr><th>Open licence</th><th>Open documentation</th><th>Local assembly</th><th>Capacity for local manufacturing</th></tr>
<tr><td>Makerbot Replicator+ | Org. A</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Makerbot Replicator Mini | Org. B</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cubex Duo | Org. A</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Ultimaker 2 | Org. C</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>Lulzbot Taz 6 | Org. D</td><td>X</td><td></td><td>X</td><td></td></tr>
<tr><td>Ultimaker Original | Org. C</td><td>X</td><td></td><td>X</td><td></td></tr>
</table>

Original Prusa i3 MK3 | Org. B	X	X	X	
Creality 3D Ender-3 | Org. A	X	X	X	
Prusa i3 | Org. E, F	X	X	X	X (partially)

The methodological steps of our study are summarised in Figure 1. In the next section, we critically discuss the results from the application of the MCT at different phases of the 3D printers' life cycle and identify hotspots and areas for improvement for sustainable degrowth and localisation.

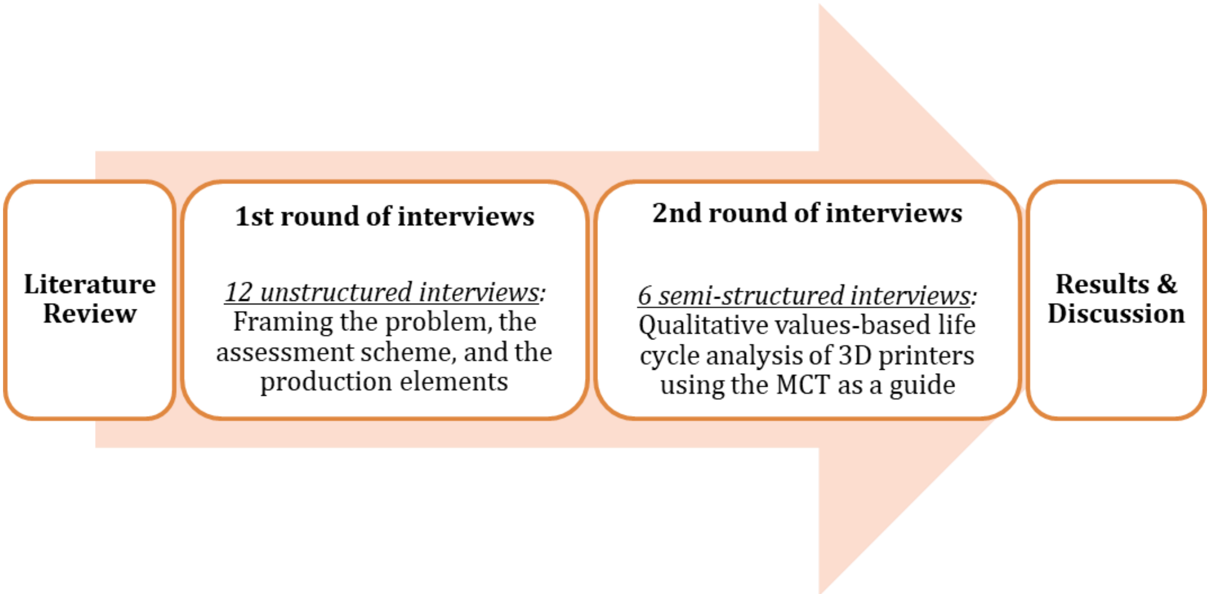

Figure 1. Methodological steps followed during the research process

4. Results and Discussion

Below we discuss our findings based on our interviews with the six organisations which were complemented with insights from the first round of interviews. The results are categorised in different life cycle stages of a 3D printer using the life-cycle dimensions of the MCT as a guide.

4.1. Assessment per life cycle stage of 3D printers

4.1.1 Acquisition and disposal of materials

The interviewees have used both proprietary and open-source 3D printers. In most cases, even open-source 3D printers were purchased from the market, either pre-assembled or as kits. Some, like Organisation F and respondents from the preliminary inquiry, had actually built a 3D printer from scratch using open-source designs.

Most interviewees found the values of the MCT for the acquisition and disposal of 3D printers' materials (Appendix D, Figure D1) irrelevant as they had no or little involvement in these processes. This was expected in the case of industrially-produced 3D printers, where the user is not involved in the production process, let alone in the acquisition of 3D printers' materials. However, even for self-built 3D printers, certain components, such as the extruder, the heated bed, and the motherboard, are purchased off-the-shelf, and the local manufacturing process starts after this point. Some parts of the 3D printer are indeed manufactured locally by another 3D printer. For these printed parts, recycled Polyethylene Terephthalate (PET) may be used, e.g. by turning a PET bottle into filament. Makers can also choose the material in certain components, such as the frame (e.g. aluminium, wood or printed), according to their needs. They also select which parts and components to purchase among the available products in the market. These options enhance to some extent the adaptability of the machine to local contexts and needs, and the relatedness of the makers-user with the 3D printer. Still, the maker mostly interacts with ready-made components and parts, which obstructs the active participation of users in the materials acquisition.

Regarding the end-of-life of 3D printers, interviewees mentioned that 3D printers are quite durable machines if properly maintained. This has been reported for both industrially-produced (like Makerbot and Prusa Research models) and locally-manufactured machines (like Prusa variants manufactured by Organisation F). When they reach their end-of-life, however, access to the disposal processes of 3D printers' raw materials proved to be challenging.

Restrictions related to the acquisition and disposal of 3D printers' materials start from the fact that the bill of materials is unavailable to the users, especially in the case of industrially-produced machines. Interviewees also noted the absence of information and infrastructure for the recycle process of 3D printers. In the best case, more experienced users were able to reuse certain parts of old models to fix or make new 3D printers. This is most common for locally manufactured 3D printers, as industrially-produced printers have limited compatibility with later models. In other cases, older machines, especially locally manufactured ones, sit in the loft of makerspaces in a museum-like fashion, exhibiting the history of the organisation. Consequently, for the time being, many interviewees have been able to adapt the 3D printer's end-of-life to their needs and abilities - mostly in the case of DGML 3D printers. They have thus avoided directly disposing of old 3D printers, which contain toxic materials (e.g. in their electronics) and shouldn't be landfilled or incinerated.

Nevertheless, the disposal of 3D printers has not been a subject of concern for most interviewees. Instead, interviewees were mainly concerned with the handling of waste created during the use of the 3D printer, i.e. how to recycle the filament (part of the 3D printing infrastructure) from failed prints (see 4.1.3). However, as 3D printing technology is evolving, more machines reach their end-of-life stage and the disposal of 3D printers will become a pressing issue. To this end, the transparency of information around the acquisition and disposal processes of 3D printers' materials and the increased user awareness associated with DGML 3D printers could create favourable conditions for the sustainable end-of-life of 3D printers.

4.1.2. Manufacturing and assembly of parts

Our survey indicates that transitioning from open licence and open documentation to actual local manufacturing of 3D printers is hard to materialise. We identified two challenging aspects: i) manufacturing and assembling a well-calibrated 3D printer requires considerable expertise, and ii) most parts are currently only produced in a centralised, industrial setting.

Concerning the first aspect, practitioners reported that manufacturing a 3D printer is a demanding venture. Multi-disciplinary skills are required (including mechanical, electronics and programming ones), which are difficult for one person to master sufficiently to be able to make a fully functional 3D printer. Those who undertake this task outside industrial settings are usually hobbyists, who are tolerant of ending up with a machine that needs frequent user intervention. The lack of safeguards and the need for manual calibration are two main reasons why accessibility is reduced for inexperienced users in the case of locally manufactured 3D printers.

The case of Organisation F, however, prefigures a potentially sustainable business model for the localised production of 3D printers. They have managed to add automatic calibration (auto-bed-levelling) and simple safeguards to their 3D printers -as industrial manufacturers do- to address some of the aforementioned problems. More importantly, rather than just selling locally manufactured 3D printers, they organise hands-on workshops where they train their customers how to assemble their 3D printer themselves for a small additional fee. A support network is created among the organisation and workshop participants, which facilitates the provision of advisory and maintenance services.

While Organisation F's business model could not be sustained for long due to changes in the Greek socio-technical landscape, experience from other DGML cases in literature shows that such initiatives can survive provided they have minimal institutional support. More specifically, the practice of offering hands-on manufacturing workshops is a typical approach for spreading DGML technologies, as manifested in the case of locally manufactured small wind turbines (Troullaki et al., 2022) or agricultural tools (Giotitsas, 2019). Such cases indicate that active participation in the manufacturing processes of a technology enhances accessibility during the use and maintenance phase.

Regarding the second challenge for the localisation of 3D printers, local manufacturing is currently associated only with certain parts of the 3D printer -mainly those that can be printed by another 3D printer. Besides these printed parts, most other parts are bought off-the-shelf from industrial suppliers. Even simple components (such as screws and ground rods) are usually ordered from abroad, while specialised mechanical and electronic components (such as extruders, controllers, and heatbeds) are sourced from overseas suppliers. Although the latter may be available in the closest urban centre, makers usually order cheap components from China. Electronics may be partially self-manufactured (parts like capacitors and boards still have to be ordered from China) but the time, effort, and money needed to build them makes this a non-viable option even for experienced makers.

Reflecting on the MCT values, relatedness, access, and adaptability at the manufacturing phase were reported as minimal for industrially-produced, pre-assembled 3D printers. Further, their level of appropriateness and bio-interaction could not be adequately answered since the interviewees had no role in the manufacturing process. Regardless of their licence types, most of these machines are rather fixed with limited adaptability after manufacturing. However, some differences are observed for ‘fully open-source” models, i.e. those that combine open licence and open documentation. Fully open-source 3D printers, such as Prusa Research products, were reported as significantly more affordable - thus more accessible in this regard- than equivalent proprietary or partially open-source ones. Additionally, fully open-source models tend to be more modular and adaptable after manufacture, as user intervention is intended and required in contrast to the “plug’n’play” proprietary alternatives.

In the case of open-source 3D printer kits, the interviewees reported limited relatedness and access to the manufacturing phase which generally remains a centralised process. They could, however, relate to MCT values when assembly is concerned. They characterised assembly as a standardised process that leaves scarce room for creativity or for building human relations, as people typically purchase a kit and assemble it themselves. Nevertheless, when the assembly is done in the context of a training workshop, as in the case of Organisation F, relations between workshop participants and organisers are created. Also, assembling 3D printer parts can be a learning, skill-building experience. Indicatively, some interviewees highlighted that the assembly process of 3D printers offers you ‘inside knowledge’ of the machine you are going to use, which is useful for fixing problems -even for proprietary 3D printers.

Access in terms of cost varies widely for different kits, with some fully open-source kits being priced significantly lower than partially open-source or proprietary ones, while reportedly having equivalent performance. Purchasing a kit though is in general cheaper than buying a pre-assembled 3D printer. The adaptability, bio-interaction, and appropriateness of 3D printer kits are to a large extent predefined by the manufacturing company, and they don’t necessarily differ from pre-assembled 3D printers in this regard. In terms of adaptability though, the interviewees mentioned that assembly is possible in any protected space without the need for special tools.

Self-manufactured 3D printers involve deep engagement from makers. Much expertise and creativity is required to choose, collect, and make the different components, to install or modify the firmware and software, and to calibrate the machine. Although access to manufacturing is closely related with the existence of open licences and documentation for 3D printers, their availability does not guarantee accessibility to the manufacturing of 3D printers. Self-manufactured 3D printers can hardly live up to the term ‘locally manufactured’ of the DGML configuration since access to the manufacturing process of most 3D printer components remains concealed. Hence, certain components end up being industrially manufactured.

Self-manufactured 3D printers are not necessarily more accessible in terms of cost compared to purchasing the same open-source model directly from the manufacturing company. Similarly, regarding bio-interaction, the expected resource-use reduction doesn’t seem to be achieved since many components are still purchased off-the shelf from overseas manufacturers. Even in the case of Organisation F that most approximates the DGML configuration, materials are transported over long distances, leading to high ecological footprints and obscure supply chains. Also, reducing the actual manufacturing process to few components reduces the relatedness of the maker with the materiality of the technological artefact, typical in the making of less sophisticated types of technology. Still, practitioners consider these “self-manufactured” 3D printers as personal creations, especially if they have also modified their designs.

To sum up, there are benefits in terms of cost and modularity in the case of fully open-source 3D printers, as well as advantages in terms of relatedness, accessibility, and adaptability that arise from the local assembly or the partially local manufacturing of 3D printers. However, manufacturing a 3D printer in the Greek context remains to a large extent dependent on centralised, standardised, and industrialised processes, limiting additional benefits, especially when referring to the bio-interaction and appropriateness of the manufacturing phase.

4.1.3. Use and maintenance

Industrially-produced pre-assembled 3D printers were reported as fairly easy to use. In fact, manufacturing companies design and market 3D printers as “plug’n’play”, i.e. ready for use with minimal user intervention required. To this end, they include additional user-friendly features that expedite problem-solving processes, such as error identification systems or heated and protective enclosure cases that help address humidity-related issues during operation.

On the other hand, access to their maintenance is restricted. An experienced user may learn basic maintenance, but when a part of a proprietary 3D printer becomes defective, it cannot be fixed. The whole part has to be replaced, which increases the cost and downtime for maintenance. The need for foreign experts in this case is evident since spare parts are only provided by the manufacturing company. A critical factor is then the quality of the company’s support, which can cause lengthy delays in communication and the shipping of spare parts overseas. Restricted access to maintenance is also reflected in the 3D printers’ appearance; they are “closed like a fridge” as an interviewee stated, consisting of non-visible parts. However, in case the printer features error identification, solutions for some hardware failures may be found through online communities.

Problems related to software and firmware cannot be fixed by users but need to be centrally addressed through the company or an official in-country service centre. Interviewees reported that depending on the success of each 3D printer model, regional or national support networks may develop; however, this has not happened in the Greek context for the examined proprietary printers. Thus, maintenance for proprietary 3D printers in the Greek context tends to be centralised with more extended and less sustainable logistics compared to certain open-source alternatives.

The differentiating factor for better access to maintenance is the presence of a large community of users sharing designs, maintenance advice, and technical information for a particular model -which is larger for some successful open-source models, such as the Prusa i3. Relatedness among 3D printers practitioners is enhanced in this case. While such communities are typical for open-source technologies, they also exist for proprietary 3D printer models. This seems to stem from a tradition of collaboration among 3D printer practitioners. As an interviewee characteristically stated, most companies set out as open-source start-ups and gradually transform to proprietary corporations with their products following that line of evolution, moving from fully open-source to proprietary.

Regarding adaptability during operation and maintenance, a restricting factor for various proprietary models is the need to use the manufacturing company's own filament. A workaround may be possible by adding a base to support the use of other filaments, a solution that has arisen within user communities of many proprietary models in an attempt to overcome artificial restrictions. In some cases, however, using non-original filament may compromise a proprietary 3D printer's warranty as stated by the interviewees. Additionally, the exchange of specific components (e.g. extruder, motor, and belt) may be possible but only between particular models of the same company. Regarding adaptability in terms of software, many users of proprietary 3D printers prefer to use open-source slicing software rather than the proprietary alternative provided by the printer's manufacturer. This has become possible through scripts developed by communities of users and available as digital commons, which adapt the software to particular 3D printer models.

All interviewees agreed that purchasing an open-source 3D printer as a kit enables users to better grasp how to address problems that may arise during its operation. In addition, the availability of a kit option for 3D printers allows for disassemblability that facilitates standardised automation and tooling as well as low-cost and decentralised maintenance processes. Makerbot Replicator, for example, is "like a closed box", while an Ultimaker Original (open-source model, also available as a kit) can be easily deconstructed to modular components that are fastened with magnets rather than screws. Therefore, availability as a kit enables adaptability during use and accessibility in maintenance, which in turn enhances appropriateness by allowing repair instead of recycling or disposing of defective parts.

Most users mentioned that the use of fully open-source 3D printers significantly increases relatedness through the development of collaborative processes. They also stated that accessing widely available digital resources facilitates repairability by non-experts. The existence of a large online community around open-source 3D printers can expedite problem-solving processes and enable the constant development and improvements in the performance of open-source 3D printers. Indicatively, Organisation F managed through support from online communities to solve calibration issues observed in open-source models by changing the firmware and adding automatic bed levelling to printers. Nevertheless, they highlighted the need for proper documentation and integration of best practices since they are currently compelled to search solutions in fragmented sources.

Interviewees also mentioned that, although fully open-source 3D printers may generally require more user intervention, they can rival industrially-produced proprietary ones in terms of performance. Further, they have shorter downtimes in case of failure, considering that their maintenance may be less dependent on remote experts and overseas suppliers if the user has basic knowledge to calibrate and maintain the machines. Thus, relatively experienced users have more motives to choose fully open-source 3D printers.

In addition, fully open-source 3D printers are more flexible in using spare parts that may be available locally, contributing to more sustainable logistics. More specifically, these 3D printers are designed to enhance adaptability, enabling the use of different filament materials (by adapting different nozzles). Proprietary models tend to be more specialised in their functionality instead (e.g. Makerbot 3D printers print only with PLA). Further, opting for more frugal and modular designs increases accessibility to maintenance, as in the case of the Prusa model compared to other proprietary and partially open-source printers. This is crucial especially in the case of sophisticated types of technology like 3D printers since it could decrease complexity and technical obsolescence (Zoellick and Bisht, 2018), leading to more affordable and environmentally sustainable 3D printers.

Regarding self-manufactured 3D printers, interviewees stressed that participation in the production process enables the comprehensibility of the produced technology -with obvious benefits for educational purposes and experimentation, but also for operation and maintenance. More specifically, practitioners who had hands-on manufacturing experience with 3D printers were more attentive to all 3D printers they use in terms of preventive maintenance, resulting in better performing machines and fewer failed prints. This indicates how important the user profile is in the performance and ultimately the ecological sustainability of the printing process. In this respect, approaching the user profile of a maker (or if we may say, a DGML actor) can be a strong leverage point for more sustainable 3D printing practices. In addition, local manufacturing organisations (like Organisation F) typically provide technical service for 3D printers locally, given that many 3D printing companies have insufficient service networks in Greece. Thus, the expertise gained through local production also fosters the creation of local maintenance networks.

As for the ecological aspects of bio-interaction and appropriateness, it is not clear whether manufacturing a 3D printer ‘locally’ -to the extent done today- reduces the overall carbon footprint emissions. Parts of the self-manufactured 3D printers still have to travel overseas from suppliers (usually China) to the end-user. However, industrially-produced 3D printers and their spare parts travel an additional route from the suppliers to the manufacturer’s premises, before reaching the end-user. Depending on the relative distances between these three locations, this may considerably increase transportation routes. The mode of transport in these overseas itineraries also needs to be considered in a context-specific manner.

In general, the interviewees did not consider 3D printers as a technology that benefits the environment; unless filament produced from recycled plastic is used. They were greatly interested in addressing ecological issues related to the operation of 3D printers, including the use of recyclable materials and the utilisation of the filament spools and the filament coming from failed prints. Although few had experimented with the disposal of wasted filament (PLA or ABS) following online instructions, manuals, and standardised recycling rules, they reported the absence of institutionalised infrastructure to utilise filament coming from unsuccessful prints. Thus, acquiring and disposing of 3D printing filament remains a centralised, industrialised, and market-driven process. In Figure 2, our findings for the three stages of the 3D printer life cycle are summarised.

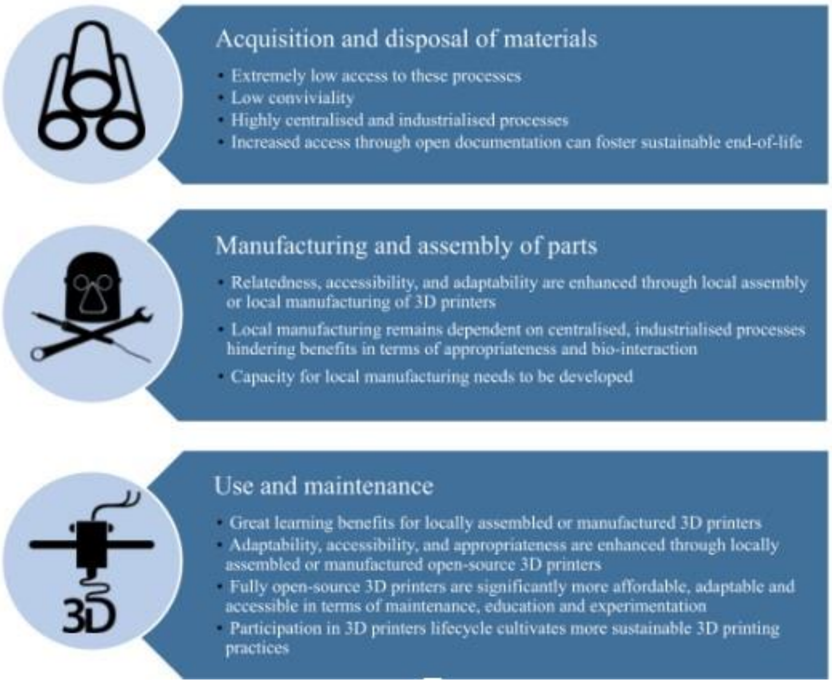

Figure 2. Summary of MCT findings for the 3D printers life cycle

4.2. Discussion

While 3D printers have been selected as a potential exemplar of DGML production, this study indicates that until now they are only to some extent compatible with the theoretical DGML conceptualisation, particularly the “manufacture local” part. 3D printers are a typical technology that develops through a global community of practitioners, companies, and associations, making them characteristic examples of the “design global” aspect. On the contrary, 3D printers’ material acquisition and manufacturing are less decentralised, and their dependence on global supply chains harder to overcome.

A main reason for that may be the fact that 3D printers are more sophisticated technologies in their manufacturing than other DGML technologies that have been examined so far, such as locally manufactured small wind turbines (Troullaki et al., 2022) or agricultural tools (Giotitsas, 2019). 3D printers include components, like motors, controllers and electronic boards that are usually inaccessible or inconvenient to self-manufacture. In addition, special emphasis should be placed on the context in which a 3D printer is developed. This is closely related to the local capacity for manufacturing, i.e. infrastructural, human, natural, and organisational elements required for localising the manufacturing of 3D printers. The combinations of such elements, however, may differ substantially from place to place. In that regard, the low local capacity for manufacturing DGML 3D printers in the Greek context does not eliminate the possibility to build fully DGML 3D printers elsewhere.

With regards to the production process of 3D printers, a main outcome of this research is that there is no consensus on specific elements that characterise an open-source 3D printer.

The distinction between open-source and proprietary 3D printers caused confusion as the definition of openness remains vague, while solely the presence of an open licence practically makes no difference to the end user. Nevertheless, there proved to be substantial differences among various open-source 3D printers when considering the combined presence of the openness elements we had defined, i.e. open licence and open documentation.

The ambiguity of the open-source concept arising from a broad spectrum of openness degrees that characterises open-source 3D printers makes the issue of openwashing relevant. Openwashing is reported when the public disagrees with an organisation's claim of offering design information fully (Heimstädt, 2017; Heimstädt et al., 2014; Tkacz, 2012). This may be due to their different expectations around the proper sharing of information in a transparent manner. For example, in the case of 3D printers, a company may release the printer under an open licence but never make its design files, bill of materials, and assembly instructions available. Hence, creating a shared understanding of standards and specifications in open-source artefacts is essential for their sustainable localisation (Bonvoisin et al., 2020).

Although motives for manufacturing 3D printers locally in non-industrial settings are currently low in the Greek territory, there seem to be motives for individuals to purchase open-source 3D printers instead of proprietary ones. That is mainly because fully open-source 3D printers are significantly more affordable and accessible in terms of maintenance, education and experimentation. In addition, the existence of digitally connected communities of users and the disassemblability of the 3D printers into modular components facilitate problem-solving and allow for open-source printers' constant development.

Nevertheless, our research shows that simply purchasing an open-source 3D printer without engaging in its lifecycle process eliminates possible benefits. More specifically, the interviewees stressed the significant role that the user profile plays in the performance and ultimately the ecological sustainability of the printers. Experienced users make fewer unsuccessful prints, minimising wasted material and electricity consumption required for printing objects. From an environmental point of view, this is crucial given the high amounts of electricity consumption of 3D printers (Ajay et al., 2016). In addition, users with hands-on manufacturing experience with 3D printers proved to be more attentive in terms of preventive maintenance, resulting in better performing machines and more sustainable 3D printing practices.

Finally, the localisation of materials has received little attention up to now, as proponents of decentralised and democratised technology usually focus on the manufacturing phase, neglecting the source of materials. Positive exceptions are open-source platforms like Materiom[1] that can offer valuable insights on producing materials locally, enhancing further the localisation of 3D printers. In addition, widely-spread bottom-up initiatives in Europe, like Precious Plastics[2], enable distributed recycling and can be attached to additive manufacturing by using plastic waste and converting it to 3D printing filament. As long as the extraction, processing, and disposal of resources remain obscure and highly complex, the prospect of

[1] https://materiom.org/
[2] https://preciousplastic.com/

establishing sustainable production cycles remains out of reach. In that sense, the decentralisation and democratisation of materials production and disposal seems of utmost importance in the pursuit of sustainable localisation for most technologies.

5. Conclusions

This paper explores the potential for a transition to sustainable degrowth and localisation through an emerging production configuration. This configuration, tentatively called DGML, requires shifting towards a political economy framework that places the commons into its core, fostering global collaboration and decentralised production with long-term benefits for society. To this end, emblematic technologies, such as 3D printers, are put forward to promote sustainable pathways for localisation and distributed production processes.

We qualitatively assessed the compatibility of differently produced desktop 3D printers with sustainable degrowth and localisation during their life cycles. We hypothesised that 3D printers produced in a DGML way would be more compatible with sustainable localisation and degrowth throughout their life cycles. To test this assumption, we conducted a series of interviews with practitioners, applying the MCT as a values-based assessment tool. The MCT helped us highlight degrowth-inspired sustainability issues related to the life cycle of 3D printers, indicating hotspots for improvement in different life cycle stages. To distinguish different production models of 3D printers, we identified four basic elements: i) the type of licence used, ii) the availability of open documentation, iii) the availability of a kit option, and iv) the capacity for local manufacturing.

While 3D printers whose life cycle is closer to the DGML configuration proved to be more compatible with sustainable localisation than those conventionally produced, our case illustrated that we still have no concrete examples of actual DGML production for 3D printers. This research featured a lack of makers' participation in a significant amount of the printers' life cycle -which is instead highly industrialised and standardised-, indicating the weaknesses of 3D printers as a technology for sustainable localisation. More specifically, the interviewees had no direct experience with the production of materials and a large part of the printer's manufacturing process, even when they were attempting to self-manufacture a 3D printer.

On a more grounded level, this study reveals that transitioning from open-source licence to truly open documentation and from open documentation to local manufacturing is challenging. There are only slight differences for users between 3D printers with an open licence and proprietary ones. The existence of a broad spectrum of openness degrees may complicate the distinction between what is open-source and what is not, making the issue of openwashing relevant.

In its current form, open documentation of relevant processes is an essential but not sufficient condition to enable users to self-manufacture a 3D printer. Local capacity for manufacturing, i.e. the local availability of multiple resources, such as skills, infrastructure, and raw materials, is required to localise the lifecycle of 3D printers. Specific steps need to be taken in this direction: more access to production processes and information; proper organisation for small-scale production of components and materials currently produced in a centralised manner; more support for citizen initiatives; and communal production infrastructures to boost mass small-scale production processes. These steps could support more sustainable technology development over time, facilitating localised manufacturing and maintenance of 3D printers with non-patented designs that promote adaptations to local contexts and the creation of local supply chains.

For future research, we would encourage investigating whether the values shared by grassroots 3D printing communities align with the MCT's degrowth-oriented principles and exploring 3D printing communities based in different regions, given the variations among regional supply chains, and the impact of cultural diversity on shaping the goals and approaches of relevant initiatives. Further, different types of technology may require different conditions for sustainability through DGML to work. Thus, sustainability assessments of other types of technology, or even non-FFF models of 3D printers, should be tested to enrich the findings of this research. Last but not least, a sample size of six organisations is sufficient to illustrate the sustainability potential and detect hotspots for improvement. Nevertheless, further research needs to be conducted both within and outside the Greek context to validate the results of our assessment and trace commonalities and differences with other contexts.

Finally, we acknowledge that qualitative, values-based assessment tools such as the MCT need to be complemented with quantitative, impacts-based assessments to provide more in-depth and robust findings, balancing positive/objective and normative/subjective sustainability issues. However, considering the limited presence of values-based approaches in sustainability assessment literature, this study attempted to fill this gap by focusing on values throughout the life cycle as an initial step.

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Appendices

Appendix A

Table A1. Literature review on the sustainability potential of 3D printers

	Reference	**Sustainability dimensions**	**Systems compared**	**3D printer model**
1	Agrawal and Vinodh (2019)	Environmental, social, economic	-	-
2	Kreiger and Pearce (2013a)	Environmental	Distributed manufacturing | Conventional manufacturing	Prusa Mendell RepRap
3	Kreiger and Pearce (2013b)	Environmental	Distributed manufacturing | Conventional manufacturing	RepRap (Prusa Mendell variant)
4	Petersen and Pearce (2017)	Economic	Home manufacturing with open-source 3D printer | purchasing	Lulzbot Mini
5	Faludi et al. (2015)	Environmental	Additive manufacturing (FDM and Inkjet) | Manufacturing with traditional machining	Dimension 1200BST FDM machine | Objet Connex 350 inkjet machine

6	Li et al. (2017)	Economic, environmental	FDM, Stereolithography and Polyjet printing	Makerbot Replicator, Makerbot Replicator 2X, Formlabs Form 1+, Stratasys Objet260
7	Wittbrodt et al. (2013)	Economic	Distributed manufacturing | purchasing	A variant of the Prusa Mendel RepRap
8	Gebler, Uiterkamp and Visser (2014)	Environmental, social, economic	3D printing | conventional manufacturing	-
9	Minetola and Eyers (2018)	Economic	Make-To-Order manufacturing by 3D printing | Make-To-Stock manufacturing using Injection Moulding	Makerbot Replicator 5th Generation
10	Ma et al. (2018)	Environmental, social, economic	-	MakerGear M2e FDM 3D printer
11	Pearce and Woern (2017)	Economic, technical	Distributed manufacturing | purchasing	Lulzbot Mini
12	Da Silva Barros and Zwolinski (2016)	Environmental	Personal fabrication | Industrial manufacturing	Prusa i3
13	Kellens et al. (2017)	Environmental	-	-

14	Weller, Kleer and Piller (2015)	Economic	-	-
15	Chen et al. (2015)	Environmental, social, economic	Selective laser sintering | Injection moulding	-
16	Yuan and Runze (2019)	Environmental, economic	Direct metal laser sintering	
17	Huang et al. (2017)	Environmental, economic	Direct metal laser sintering	
18	Matos and Jacinto (2019) | Matos et al. (2019)	Social	-	-
19	Lindemann et al. (2015)	Economic, technical	-	-
20	Khorram, et al. (2018)	Economic	Additive manufacturing | conventional manufacturing	-
21	Doran, Smullin and Haapala (2016)	Environmental, social, economic	Additive manufacturing | Subtractive manufacturing	Typical Directed Energy Deposition machine
22	Peng et al. (2018)	Environmental, social, economic	-	-
23	Hapuwatte et al. (2016)	Environmental, social, economic	Additive manufacturing | Conventional manufacturing	Metal additive manufacturing

24	Cerdas et al. (2017)		Additive manufacturing | Conventional manufacturing	Makerbot Replicator

Appendix B

Table B1. First round of interviews

Focus area	**Questions**
Model specifications	- How many different 3D printers have you used or produced? - Can you give us details about the supported materials, the print volume and the layer resolution of the 3D printer(s)?
Open-source	- Have you ever used or produced an open-source 3D printer? - Compared to an industrially-produced, proprietary 3D printer (e.g. Makerbot), have you observed any advantages/disadvantages of open-source 3D printers? - Did you make use of an open source design? Did you produce your own design?
Local Manufacturing	- What about the manufacturing process of the 3D printer? Was your 3D printer pre-assembled, did you buy it as a kit or did you manufacture it from scratch?
Time frame	- When did you first use the 3D printer? - Do you still use this 3D printer? If yes, how often?
Use-context	- Who are the users of the 3D printer? - Do you also sell 3D printers that you manufacture?
Use-purpose	- How do you use the 3D printer (e.g. educational purposes, commercial or private use)?

Maintenance	- How do you provide maintenance for these 3D printers? - Do you buy spare parts?

Appendix C

Table C1. Specifications of FFF 3D printer models recorded during the study. The models investigated during the second round of interviews are noted in grey colour

Model	Makerbot Replicator+	Cube X Duo	Craftbot Plus	Zortrax M200	Original Prusa i3 MK3	MakerGear M2	Ultimaker Original	Ultimaker 2	BCN Sigma	Lulzbot Taz 6	Stereolab Prusa i3
Manufacturer (Location)	Makerbot (USA)	3D Systems (USA)	Craft Unique (Hungary)	Zortrax S.A. (Poland)	Prusa Research (Czech Republic)	MakerGear (USA)	Ultimaker (Netherlands)	Ultimaker (Netherlands)	BCN 3D Technologies (Spain)	Aleph Objects (USA)	Stereolab (Greece)
Licence	Proprietary	Proprietary	Proprietary	Proprietary	Open-source	Open-source	Open-source	Open-source	Open-source	Open-source	Open-source
Designs	Closed	Closed	Closed	Closed	Closed	*Open (partially)*	*Open* (source files open after next model is out)	*Open* (source files open after next model is out)	*Open* (source files open after some time)	Open	Open
Kit option	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes
User participation in production option	No	No	No	No	No	No	No	No	No	No	Yes

Third-party filament	*Yes* but compromises warranty	No	Yes	Yes	Yes	*Yes* but compromises warranty and support	*Yes* but may compromise warranty	*Yes* but may compromise warranty	*Yes* but compromises warranty	Yes	Yes
Weight	18.3 kg	37 kg	14.45 kg	16 kg	~6.5 kg	12 kg	10.5 kg	11.2 kg	15 kg	14.97 kg	~6.5 kg
Build volume	295x195x165mm	275x265x240 mm	250x200x200 mm	200x200x180mm	250x210x210mm	254x203x203mm	210x210x205 mm	223x223x205 mm	210x297x210mm	280x250x280mm	200x200x200mm (300x200x200 mm)
Extruder	Single	Dual	Single	Single	Single	Single	Single	Single	Dual	Single	Single
Screen	LCD screen	LCD touch screen	Color LCD touchscreen	IPS touchscreen	LCD screen	No	Yes	Yes	Color LCD touch screen	Yes	Optional
Price	€2500 - 3000	$999 (Production stopped)	$1500	~ €2000	~ €770-1000	$2000	~ €1000	~ €2500	€2475	~ €2500	€487-658

Appendix D

MATERIALS							
Harvesting, processing and disposal of raw matter							
Energy carriers (electricity, fuel, etc.) and materials (steel, copper, plastic, etc.)							
RELATEDNESS What relations does it create for people?	Process fixed	☐	☐	☐	☐	☐	Right to creative input
	Market-driven	☐	☐	☐	☐	☐	Need-driven
ACCESS Who can produce/dispose it where and how?	Secret or patented	☐	☐	☐	☐	☐	Knowledge freely accessible
ADAPTABILITY How independent and linkable is it?	Special machines	☐	☐	☐	☐	☐	Everyday tools
	Special materials	☐	☐	☐	☐	☐	Common materials
BIO-INTERACTION How does it interact with living organisms?	Deteriorating soil, air and water	☐	☐	☐	☐	☐	Improving soil, air and water
	Toxic waste	☐	☐	☐	☐	☐	Biodegradable
APPROPRIATENESS What is the relation between input and output considering the context?	Far away	☐	☐	☐	☐	☐	Locally available
	New	☐	☐	☐	☐	☐	Re-used
	Non recyclable	☐	☐	☐	☐	☐	Easily recyclable

Figure D1. Adapted version of the MCT - Materials

MANUFACTURING							
Assembling raw materials and preproducts							
Manufacturing of parts (electronic, mechanical, printed, etc.) and their assembly							
RELATEDNESS What relations does it create for people?	Process fixed	☐	☐	☐	☐	☐	Right to creative input and skill building
	Needs painful worktime	☐	☐	☐	☐	☐	Allows joyful worktime
	Individual process	☐	☐	☐	☐	☐	Collaborative process
ACCESS Who can produce it where and how?	Cost intensive	☐	☐	☐	☐	☐	Low Cost
	Secret or patented	☐	☐	☐	☐	☐	Knowledge freely accessible
ADAPTABILITY How independent and linkable is it?	Big scale economical	☐	☐	☐	☐	☐	Small scale economical
	Special conditions	☐	☐	☐	☐	☐	Everywhere possible
	One piece/Fixed once finished	☐	☐	☐	☐	☐	Modular
BIO-INTERACTION How does it interact with living organisms?	Deteriorating soil, air and water	☐	☐	☐	☐	☐	Improving soil, air and water
	Hazardous potential	☐	☐	☐	☐	☐	Safety proven and tested
APPROPRIATENESS What is the relation between input and output considering the context?	Creates waste	☐	☐	☐	☐	☐	Byproducts are used

Figure D2. Adapted version of the MCT - Manufacturing

USE							
Procuring the task it was built for							
Operation and maintenance of the 3D printer and the 3D printing filament							
RELATEDNESS What relations does it create for people?	Creates distance	☐	☐	☐	☐	☐	Supports collaboration
	Needs painful worktime	☐	☐	☐	☐	☐	Allows joyful worktime
ACCESS Who can use it where and how?	Cost intensive	☐	☐	☐	☐	☐	Low Cost
	Abstract	☐	☐	☐	☐	☐	Comprehensible
	Need of foreign experts	☐	☐	☐	☐	☐	Use of local knowledge
ADAPTABILITY How independent and linkable is it?	Not able to fulfill needs	☐	☐	☐	☐	☐	Able to fulfill needs
	Requires specific filament	☐	☐	☐	☐	☐	Encourages diversity
	Special conditions	☐	☐	☐	☐	☐	Everywhere possible
	Repairable by experts	☐	☐	☐	☐	☐	Repairable by skilled
BIO-INTERACTION How does it interact with living organisms?	Deteriorating soil, air and water	☐	☐	☐	☐	☐	Improving soil, air and water
	Toxic waste	☐	☐	☐	☐	☐	Biodegradable/Byproducts are used
APPROPRIATENESS What is the relation between input & output considering the context?	Nondurable	☐	☐	☐	☐	☐	Durable
	High energy consumption	☐	☐	☐	☐	☐	Low energy consumption

Figure D3. Adapted version of the MCT – Use

Appendix E

Table E1. List of names and activities of the organisations included in the study

Organisations	Activity
Org. A	Fabrication, Education and Research laboratory
Org. B	Fab Lab (digital fabrication laboratory)
Org. C	Research collective
Org. D	Social cooperative
Org. E	Design and fabrication lab

Org. F	3D printing company, Research and Education laboratory