DOCTORAL THESIS

Envisioning Institutional Pathways for Cosmolocal Production: A Near-future Landscape Through Science and Technology Parks

Nikiforos Tsiouris

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TALLINN UNIVERSITY OF TECHNOLOGY
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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Nikiforos Tsiouris

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Kosmolokaalse tootmise institutsionaalsete teede kavandamine: lähituleviku maastik teadus- ja tehnoloogiaparkide kaudu

NIKIFOROS TSIOURIS

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List of publications

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III Kostakis, V., & **Tsiouris, N.** (2024). How to unite local initiatives for a more sustainable global future. *Sustainable Futures, 7*, 100187. **ETIS 1.1.**

IV **Tsiouris, N.** (2024). An Alternative Approach to Science and Technology Parks. *Postdigital Science and Education*, 1-16. **ETIS 1.1.**

Author’s contribution to the publications

Contribution to the papers in this thesis are:

I The author of the thesis contributed in this article with insights due to his engineering background and his previous experience with digital technologies in construction. The author was involved in the following processes: writing, reviewing and editing the final manuscript, coordinating the revisions, project administration and visualization.

II The author of the thesis contributed to the theoretical framework, developing the degrowth and localization aspects of the theory. The author was involved in analysing the data gathered from the interviews and their interpretation, drafting the manuscript and revising the final accepted version.

III The author of the thesis was responsible for project administration, addressing the reviews and revising the final manuscript. The authors collaborated and combined insights from their fieldwork with grassroots initiatives that organize around the commons.

IV The author of the thesis was solely responsible for the research design and development, the conduction of case study research, the write-up and revisions of the manuscript and correspondence.

Abbreviations

BIM	Building Information Modelling
CNC	Computer Numerically Controlled
DGML	Design Global, Manufacture Local
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FOSS	Free and Open-Source Software
GDP	Gross Domestic Product
ICT	Information Communication Technologies
LCA	Life Cycle Assessment
MCT	Matrix of Convivial Technology
R&D	Research and Development
OBS	Open Building Systems
OCS	Open Construction Systems
STP	Science and Technology Park
3D	Three-dimensional

Preface

Prior to pursuing a doctoral degree in social sciences, I was most recently involved in two different fields: civil engineering and football. However unrelated these two domains may seem, they share a crucial, devastating connection. They are both major contributors to the unprecedented existential crisis humanity is facing. Civil engineering through building construction is one of the most wasteful, polluting and emissions-intensive industries, accounting for 39% of global carbon emissions (Abergel et al., 2017). Similarly, football provides a magnified view, due to its popularity, of the steep socio-economic inequalities that deepen uncontrollably. A prime example is the Qatar 2022 World Cup, which involved corruption scandals, vast environmental damage and social controversies due to the proven exploitation of migrant workers (Paché, 2020).

From day one in engineering school, we were instilled with the idea that engineers are problem-solvers, specialists in providing the optimal cost- and time-efficient solutions for each project. It was as if cost and time were the only objective parameters that mattered. Civil engineering is a vast field, ranging from house construction to highways, bridges, and underwater tunnels. It carries huge implications not only for individuals' lives but for entire societies and their ecosystems. How can such complex and multifaceted issues be reduced to merely a cost- and time-efficiency problem?

Instead of nurturing new generations of engineers to bloom by stimulating critical thinking, engineering schools cultivate a monoculture of 'efficient' project managers – neutral, objective implementers. But humans can be neither neutral nor objective. Engineering practitioners and educators are often fond of the idea that technique is neutral and demands experts who know what needs to be done (Saltelli et al., 2020). Meanwhile, the dense web of trade-offs, conflicting interests and externalities are implicitly ignored or explicitly disregarded (Taleb, 2012).

However, I cannot ignore or disregard issues that largely contribute to the exploitation of humans and all other natural life. This conviction has led me to pursue a PhD in social sciences, where I aim to follow a pathway that makes me part of the solution, not the problem. Through my doctoral research, I seek to understand and address these systemic challenges, though I am not sure how well, if at all, I am fulfilling this purpose. Nevertheless, I will certainly keep trying. After all, even amid grave challenges, we are staggering forward.

Introduction: Scope, aim and structure of the thesis

Our society, under prevalent institutional settings, seems to have reached a point where it is difficult to admit that we do not have a solution for every problem (Guimarães Pereira & Funtowicz, 2015). Evidently though, we have yet to solve the unprecedented environmental and socio-economic challenges that humanity faces, including climate crisis, resource depletion, and deepening global inequalities (Lange et al., 2020; Sovacool et al., 2020). There is now certainty that the prevailing modus operandi of technology development and production models, burdened with profit-maximization, planned obsolescence, and environmentally harmful practices, is exacerbating rather than mitigating these issues (Kostakis et al., 2018; **III**; **IV**). The gravity of this crisis has spurred interest in alternative paradigms that could foster more sustainable and fairer forms of technological innovation.

This thesis was motivated by academic, professional, and social experiences that prompted an exploration of alternative approaches to technology development. Through interactions with diverse communities, it became apparent that such alternatives already exist, leading to the decision to study one in particular. This thesis examines a production configuration that leverages global knowledge to enable communities to fulfill their needs through the co-management of shared resources while minimizing their socio-environmental impact – cosmolocal production (Kostakis 2023a; Troullaki et al., 2022; **III**). Furthermore, it attempts to outline the contours of an institution that could foster such a configuration: a science and technology park (STP). STPs have traditionally catalyzed technology development by serving as clusters of innovation and multi-stakeholder collaboration (Laspia et al., 2021). They are socio-technical infrastructures where technology, governance, and business converge, making them suitable experimental testbeds for an emerging production configuration.

This thesis is situated within social sciences, specifically in the field of science and technology studies. Its impetus has arisen from the need for sustainable technology development amidst a grave socio-environmental crisis. It focuses on cosmolocal production, which has been investigated in various settings: the construction sector (**I**), the 3D printers' supply chain (**II**), and an ecosystem of grassroots initiatives (**III**). Cosmolocal production embeds multiple elements that have been receiving increasing attention for their sustainability potential, such as open-source technologies, convivial innovation, needs-based design, and localized manufacturing.

At the core of this thesis is cosmolocal production, and one of the main challenges is its uptake at an institutional level. This thesis focuses on positioning cosmolocal production within an institutional setting – specifically, an STP. The choice of STPs derives from participatory action research with a grassroots STP-focused initiative (**IV**). However, STPs are not the final destination of this thesis; they are rather the vehicle to elaborate on the technology, business, and governance implications of cosmolocal production.

Drawing on Ostrom's work (1990; 2010; 2017), I understand an STP as a polycentric institution – a system of governance with multiple centers of decision-making that are formally independent of each other. These decision-making centers operate with some degree of autonomy but also interact under an overarching set of rules (Aligica & Tarko, 2012). STPs fit the description of a polycentric institution due to their multi-stakeholder character and complex inter- and intra-organizational processes and relations (**IV**).

To outline the contours of cosmolocal production within an STP, I employ the near-future landscape, a device used in critical future studies. These studies call for a deeper examination of the assumptions, worldviews, and power structures shaping our perceptions of the future (Slaughter, 2002). They emphasize that the future is not predetermined but actively created through our present choices. Future possibilities are shaped by long-standing social patterns and dominant cultural frameworks (Inayatullah, 1998). By surfacing and questioning the deeper layers of the status quo, we can open up new avenues for transformative change. Near-future landscapes create accessible scenarios through visual images, highlighting fundamental choices and outcomes. They may help better grasp the current predicament and identify strategies for addressing it (Bowden, 2021; Slaughter, 1997).

The main research question of this thesis is: How can cosmolocal production be institutionalized to foster sustainable socio-technical futures? Two secondary research questions that contribute to addressing the main one are the following:

- How do the principles of openness and localization in cosmolocal production impact environmental sustainability and technology development? (Articles **I**, **II**)
- What institutional arrangements and governance mechanisms could support the development of cosmolocal production? (Article **III**, **IV**)

The synthesis of the main findings is situated within broader debates about transitions toward more sustainable socio-technical systems. While acknowledging the challenges of scaling alternative approaches within dominant capitalist frameworks, the thesis argues that they offer promising pathways for technology development better aligned with pressing sustainability imperatives. The main objective is to provide a preliminary, evidence-informed understanding of cosmolocal production's sustainability dynamics in an institutional setting.

The remaining introductory part of the thesis proceeds as follows. Section 2 elaborates on the opportunities and implications of cosmolocal production, examines the institutional nature of an STP and its limitations, and introduces the theoretical tools of critical futures studies and the perspective of near-future landscapes. Section 3 describes the methodological approach and unravels the connections between the four articles. Section 4 illustrates a near-future landscape for STPs, describes its various elements, and delves into its different dimensions. Section 5 summarizes the findings and suggests areas for future research.

1 Theoretical background

1.1 Cosmolocal production in a nutshell

Cosmolocal production represents an emerging production configuration that combines global knowledge sharing with localized manufacturing to address pressing socio-environmental challenges (Kostakis et al., 2023a; **III**). This approach leverages digital commons and distributed production capabilities to create a more sustainable and equitable mode of economic organization.

At its core, cosmolocal production is grounded in the concept of the commons, i.e., social systems for collectively managing shared resources (Ostrom, 1990). It extends this notion to the digital realm, fostering global communities that collaboratively develop open-source designs, knowledge, and software as part of a digital commons (Kostakis et al., 2023a; **IV**). Simultaneously, physical production occurs locally, considering specific contextual needs and constraints.

This configuration aims to reduce material and energy footprints by enabling communities to produce goods on demand, without outsourcing negative impacts to distant ecosystems (Kostakis et al., 2023a). It utilizes the efficiency of global knowledge networks while preserving the autonomy and resilience of local production systems – an approach termed 'mid-tech' (Kostakis et al., 2023b; **III**).

Cosmolocal production aligns closely with the concept of conviviality as articulated by Ivan Illich (1973). Conviviality, if translated to the technology realm, emphasizes on sufficiency and creativity, design for affordability and durability, tacit knowledge, capacity building and localization (Ralph, 2021; **I**, **II**). By democratising access to knowledge and means of production, communities are enabled to shape tools according to their needs and values (Kostakis et al., 2023a; **I**, **III**).

Examples of cosmolocal initiatives span various domains, including open-source agricultural machinery, e.g., L'Atelier Paysan, prosthetics, e.g., OpenBionics, renewable energy systems, e.g., Wind Empowerment and space technologies, e.g., Libre Space Foundation (**III**). These projects demonstrate how global collaboration could empower local communities to develop appropriate technologies that enhance autonomy, resilience and sustainability.

However, cosmolocal production is not without tensions. While it may reduce reliance on global supply chains, it still depends on large-scale, energy-intensive digital infrastructures such as the Internet (**III**). Moreover, scaling these initiatives requires navigating complex political and institutional implications. Rather than upscaling, cosmolocal production brings forth how actors actively and deliberately work to reshape the boundaries between scales to better engage with and influence various social, economic, and political processes (Grillitsch et al., 2024; Kostakis et al., 2024b).

As with any emergent phenomenon, new policy and regulatory frameworks are necessary to enable cosmolocal production. This could be assisted by more in-depth case studies of its institutional implications and by the thorough documentation and standardization of its processes (**II**). But also in the cases of already successful cosmolocal examples, concerns have been raised about these initiatives being co-opted by the prevalent capitalist system (Agrawal, 2002; Bauwens & Jandrić, 2021; **IV**).

Despite these challenges, cosmolocal production offers a promising pathway towards a more inclusive and sustainable economic model. By fostering a production configuration based on the commons and prioritizing local needs over profit maximization, it suggests a response to the relentlessly growth-oriented logic of capitalist production (Kostakis et al., 2023a; Robra et al., 2020; **III**). As such, cosmolocal production represents an important area for further research and experimentation in the pursuit of post-growth economic alternatives.

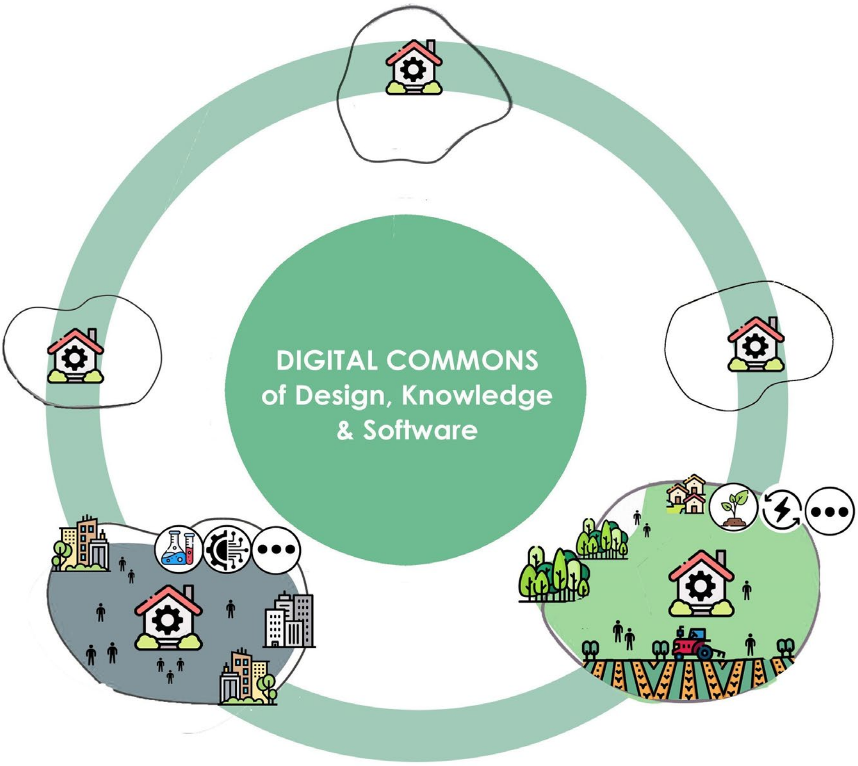


*Figure 1: The cosmolocalism structural framework with its functions (e.g., knowledge transfer), spatial dimensions (e.g., local/global, rural/urban), and main fields of activity (e.g., agriculture, digital technologies) (Kostakis et al., 2023a; **III**).*

1.2 Science and technology park, an institution not without its challenges

STPs are multi-stakeholder institutions that aim to enhance regional economic and social impact by promoting innovation and competitiveness among associated businesses and knowledge institutions (Link & Scott, 2007; IASP, 2017). They typically provide specialized infrastructure and services while fostering connections between universities, research institutes, and private organizations.

STPs employ various strategies to support technology and business development. Based on their operational approaches and focus, three distinct types can be identified. Certain STPs are research-oriented, focused on R&D activities. They include research infrastructure such as laboratories for private use and maintain strong ties with universities and research institutes. The second type prioritizes the establishment of collaborations providing shared facilities and extensive amenities. These facilitate partnerships and offer a range of administrative and consulting services. The third approach is business-oriented and its scope is to support startups through business development services, incubation services, and access to investors for funding acquisition (McCarthy et al., 2018, Ng et al., 2019).

The management and organizational structures of STPs have evolved beyond the traditional university-led approach to include various public-private partnership models. While early parks were primarily university initiatives aimed at commercializing research and generating income from land resources, modern STPs often operate under more complex governance structures involving multiple stakeholders from academia, industry, and government (Zhang, 2005). This evolution reflects their expanding role as innovation policy instruments aimed at enhancing regional economic development.

STPs have traditionally aspired to catalyze high-tech innovation and economic growth through the agglomeration and collaboration of research institutions, start-ups, and established technology firms (Laspia et al., 2021). They often focus on rapidly developing high-tech fields like biotechnology, information technology, and advanced materials (UNIDO, 2021; **IV**). While the predominant technology and business development model of STPs has managed to fulfil its purpose to a certain degree, it also indicates significant limitations in terms of social and environmental sustainability.

The conventional STP approach has a narrow focus on high-tech. It emphasizes cutting-edge technology and rapid commercialization which often leads to neglecting other forms of innovation, including social innovation and appropriate technologies adapted to local contexts (Kerschner et al., 2018). The focus on generating high-tech intellectual property and growth-oriented startups often aligns STPs with the dominant economic paradigm that prioritizes private profit over broader social and ecological well-being (**IV**).

The development of high-tech products often involves resource-intensive processes with significant environmental costs throughout their lifecycles (Lange et al., 2020; Sovacool et al., 2020). Researchers recognize a strong turn to sustainable practices in STPs' strategic policies but still a lacking implementation. Additionally, there is increasing interest from STP administration to become more extroverted toward the local society (da Costa Mineiro et al., 2024). Decision-making and access tend to be restricted to a limited set of stakeholders from academia, industry and government, excluding broader community participation (**IV**). At the same time, benefits tend to accrue mainly to a small group of highly educated knowledge workers, executives and investors (Bakouros et al., 2002; Massey & Wield, 2003).

These limitations suggest the need to reimagine STPs for the future. Research suggests that polycentric systems, characterized by multiple centers of decision-making, could be more effective in addressing complex challenges than centralized approaches (Andersson & Ostrom, 2008; Rothstein, 1998). Applied to STPs, this could mean developing more diverse and inclusive governance structures that involve a wider range of stakeholders, including local communities, civil society organizations and individuals (Ostrom, 2009). This approach resonates with the effectiveness of community-managed resources and the importance of considering multiple scales and outcomes beyond mere economic growth (Benkler, 2006; Ostrom, 1990; Schlager et al., 1994).

Furthermore, a polycentric institution should consider and address the interplay between social and ecological factors (Aligica & Tarko, 2012; Ostrom, 2010). For STPs, this could translate into a greater focus on developing technologies and innovations that address both social and environmental challenges. By incorporating a more decentralized approach, STPs could evolve into more resilient, adaptive, and inclusive institutions.

1.3 Critical futures studies and near-future landscape

Building upon critical futures studies and social constructionist perspectives (Slaughter, 2002), I leverage specific tools from the broader field to explore potential futures for STPs and cosmolocal production. This approach is grounded in the perspective that our external reality is a social construction based on beliefs and worldviews (Slaughter, 2002). Slaughter (1993) argued that future studies methods needed to focus on the inner world of individuals and societies, moving beyond traditional methods such as megatrend analysis and environmental scanning, which often overlook deeper realities.

A particularly useful concept in this context is the near-future landscape (Slaughter, 1997). Near-future landscapes are visual or conceptual representations of possible near-term futures that highlight fundamental choices and outcomes. These accessible scenarios could help stakeholders better grasp current predicaments and identify strategies for addressing them, making them especially valuable in exploring the future of a socio-technical infrastructure such as an STP.

Near-future landscapes illuminate otherwise abstract ideas and summarize a wide range of propositional or interpretative knowledge about the near-term future in ways that can be more clearly comprehended (Bowden, 2021; Slaughter, 1997). When applied to project cosmolocal production within an STP, near-future landscapes can forcefully express particular points of view about potential futures, illustrating areas of danger and opportunity. Similarly to maps, they help us plan ahead, anticipate problems, design strategies, and ‘steer’ in particular directions (Slaughter, 1997).

By employing near-future landscapes, we can make complex ideas about the future of STPs and cosmolocal production more accessible and engaging to a wider audience. This approach allows us to graphically represent interconnected aspects of the near-future context and portray contrasting forces at work in the technological and social environment. Near-future landscapes attempt to resolve certain limitations of textual representation, albeit imperfectly, yet in ways that are comprehensible to broad sections of the community (Bowden, 2021).

When done well, near-future landscapes can illuminate aspects of possible futures for STPs and cosmolocal production, and then tie these back to assumptions, ways of thinking, and decisions in the present (Slaughter, 2002). This can potentially stimulate wider consideration of challenges and more thoughtful decision-making about the implications of different pathways for STP development and cosmolocal production.

This approach aligns with the critical perspective of this thesis, as it encourages us to question existing assumptions and actively imagine alternative futures. By creating a near-future landscape for STPs that foster a cosmolocal approach, we can explore how these institutions and practices might evolve to foster more sustainable, democratic, and inclusive forms of innovation and production.

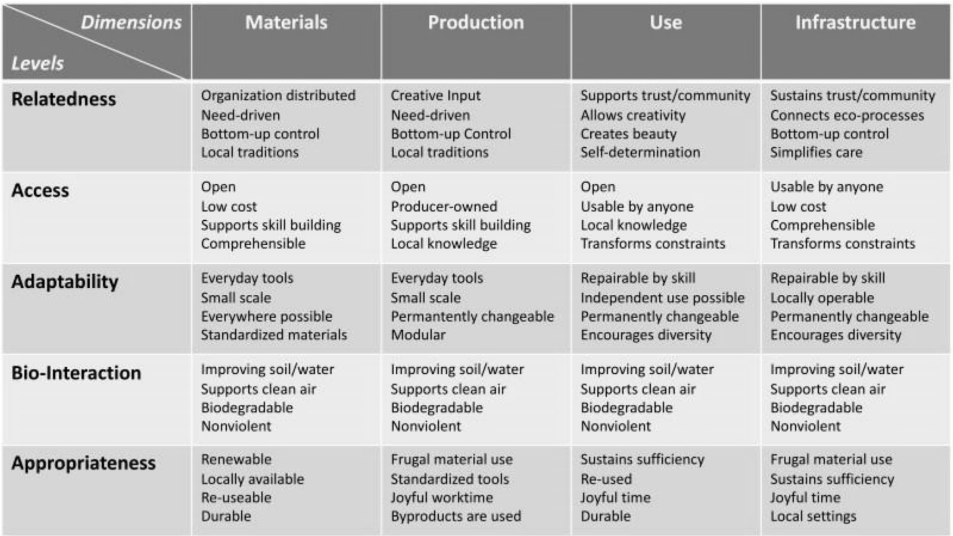
Furthermore, by uniting as a professional community and establishing formal structures to legitimize, professionalize, and promote future work, we can develop social foresight capacity (Slaughter, 2003). In the context of STPs and cosmolocal production, as I will later elaborate, this could mean bringing together diverse stakeholders – from academics and policymakers to community members and entrepreneurs – to collectively envision and collaborate towards more sustainable futures.

2 Methodological approach

At the core of this thesis are open-source technologies, cosmolocal production and the commons. I employed a qualitative methodological approach to examine how an institution like STPs could develop a mutually beneficial relationship with the aforementioned emerging phenomena, fostering their culmination while reaping their benefits. My methodology is designed to capture the complexity and diversity of these emerging practices offering an identification of, on the one hand, positive patterns and principles and, on the other hand, acknowledging challenges and limitations. Qualitative methods include semi-structured questionnaires (**II**, **IV**), interviews (**II**, **IV**), tools such as the Matrix of Convivial Technology (MCT) (**I**, **II**), and in-situ observations of relevant practices (**III**, **IV**). Throughout my research progression, I drew insights by gathering empirical data and I employed a participatory approach where case participants become contributing researchers and, hence, experts who can contribute to understanding the underlying processes (Reilly, 2010). The anticipated outcome of this methodological approach is the development of nuanced responses to the research questions. These findings are expected to contribute to the "ongoing social dialog about the problems and risks we face and how things may be done differently" (Flyvbjerg, 2001, p. 61).

Article **I** investigates the sustainability of the construction sector, which is one of the most wasteful, polluting and emissions-intensive industries (Abergel et al., 2017). The article conducts a comprehensive review of the challenges posed by conventional construction practices and assembles the potentialities of open-source convivial technologies and cosmolocal production for the construction sector. On that front, the article builds on three previously investigated cases of open construction systems, i.e. the Hexayurt, the Open Source Ecology Microhouse and the WikiHouse (Priavolou, 2018) and three interlocked elements for conviviality, i.e. modularity, sharing and adaptability (**I**). Consequently, Article **I** configures a framework of open construction systems that could foster a more democratic, inclusive and sustainable construction sector. To mitigate the ambiguity entailed in the concept of conviviality, the normative schema of MCT was employed.

*Table 1. Dimensions and levels of the MCT (**I**). Adapted from: https://www.andrereichel.de/2019/05/20/artificial-intelligence-convivial-technology/.*



Dimensions / *Levels*	Materials	Production	Use	Infrastructure
Relatedness	Organization distributed Need-driven Bottom-up control Local traditions	Creative Input Need-driven Bottom-up Control Local traditions	Supports trust/community Allows creativity Creates beauty Self-determination	Sustains trust/community Connects eco-processes Bottom-up control Simplifies care
Access	Open Low cost Supports skill building Comprehensible	Open Producer-owned Supports skill building Local knowledge	Open Usable by anyone Local knowledge Transforms constraints	Usable by anyone Low cost Comprehensible Transforms constraints
Adaptability	Everyday tools Small scale Everywhere possible Standardized materials	Everyday tools Small scale Permantently changeable Modular	Repairable by skill Independent use possible Permanently changeable Encourages diversity	Repairable by skill Locally operable Permanently changeable Encourages diversity
Bio-Interaction	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent
Appropriateness	Renewable Locally available Re-useable Durable	Frugal material use Standardized tools Joyful worktime Byproducts are used	Sustains sufficiency Re-used Joyful time Durable	Frugal material use Sustains sufficiency Joyful time Local settings

Scaling down from the general, i.e., construction sector, Article **II** delves into the more specific, i.e., the supply chain of 3D printers. This article examines the production of 3D printers and the sustainability potentialities of the different production processes, ranging from open-source and locally manufactured to industrially produced. Article **II** makes a comparative assessment of the various production processes focusing on desktop 3D printers, specifically the Fused Filament Fabrication (FFF) technology which is one of the most widely used and commercialized 3D printing applications. First, a literature review of sustainability assessments around the 3D printing technology was conducted, followed by a preliminary round of 12 interviews. The first iteration of interviews with do-it-yourself enthusiasts, individuals from maker communities, and 3D printing enterprises delivered a tentative understanding of the current status at the EU level. The inquiry focused on the manufacturing, use, maintenance and open-source elements of the 3D printers' production process. For the second round of interviews, the study was narrowed down to Greece considering the country-level specificities of technology production and supply chain management. The second round was guided by the MCT tool and consisted of 6 semi-structured interviews with makerspaces and fab labs. The six organizations cover an array of interests and functions:

1. A fab lab and MakerBot reseller
2. A digital innovation hub for prototyping and education
3. A research collective focused on experimentation and education
4. A makerspace developing innovative prototypes
5. A makerspace offering prototyping and manufacturing services
6. An open-source 3D printing company building customisable Prusa i3 variants

Article **II** identifies four key elements differentiating the 3D printer production process, two in the design and two in the manufacturing phase, which emerged from the interviews and complementary discussions and are informed by the literature. The elements are: the type of license; the availability of documentation; the availability of a kit option for local assembly; and the capacity for local manufacturing. The different studied 3D printer cases are assessed on whether they satisfy these four elements to distinguish hotspots and areas of improvement regarding the sustainability potentialities of cosmolocal production.

After drawing insights into the construction sector and the supply chain of 3D printers, Article **III** adopts an ecosystemic approach and delves deeper into cosmolocal production building on desk research and experience from the field. The article critically examines existing positivist narratives around technology development such as green growth and ecomodernism, challenging the reliance on high-tech innovations for addressing socio-environmental crises. Drawing knowledge from various fields and integrating diverse strands of thought including political ecology, STS, and sustainability studies, Article **III** presents a normative framework for technology development based on cosmolocal production. While the article does not employ empirical data or quantitative analysis, the theoretical arguments are grounded on a plethora of paradigmatic cases from the commons realm, illustrating the benefits of cosmolocal production principles in dispersed initiatives around the globe. The methodological approach in Article **III** allows the exploration of potential future pathways and policy implications. Future research could build on the conceptual foundation in this article and proceed to its empirical validation by further assessing the existing and/or new cases.

Article **IV** builds on the insights of the previous three articles, projecting them in the confined context of an STP. The study employs an exploratory case study methodology to examine an alternative approach to STPs (Yin, 2009). The research focuses on a grassroots initiative called OpenTechPark-Citizens for Open-Tech in the Region of Epirus, Greece. I adopt a participatory approach to case study research, where case participants contribute as researchers and experts. The study is based on personal observations and interpretations after documenting a year-and-a-half-long public deliberation involving various stakeholders and experts and holding iterative cycles of participant feedback to co-configure a normative framework for a commons-oriented STP, emphasising inclusivity and socio-environmental sustainability.

The cultural background of the researchers involved and the geographic limitations of the study, primarily conducted within the European context, are important factors to acknowledge as they have influenced this thesis. Each issue under examination carries political, economic, and social connotations, which this research project endeavors to comprehend while providing an in-depth analysis. Neglecting the impact of ethical and cultural specificities of different publics in the global arena can lead to significant errors in both research and practice (Saltelli et al., 2020). Consequently, investigating similar initiatives in diverse socio-economic contexts, particularly in non-Western countries, and drawing from a more diverse pool of researchers could yield additional valuable insights and perspectives.

The corpus of publications underpinning this research utilizes a diverse array of theoretical and analytical frameworks, from political ecology and engineering studies to critical technology theory and social sciences. This theoretical pluralism, in conjunction with the synthesis of data derived from case studies, brings forth a comprehensive range of perspectives. Consequently, the thesis does not only contribute to the existing body of knowledge but could also provide foundational elements for future interdisciplinary research and practical applications in sustainable technology and business development (Demaria et al., 2023; Gatto, 2020; Kothari et al., 2019).

Table 2. Overview of the four articles comprising the thesis.

Articles	Methodological approach	Outcome
I, II	**Empirical engagement** with sustainability issues in two illustrative sectors	Empirical **underpinnings of the challenges** of cosmolocal production
III	**Conceptual engagement** with a commons-based technology framework	Cosmolocal production as a **configuration to transcend sustainability** challenges
IV	**Empirical exploration** of an STP from a cosmolocal production perspective	Groundwork necessary for **cosmolocal production to emerge in an institutional setting**

3 A near-future landscape through science and technology parks

STPs have long been viewed as key drivers of innovation and economic development (Lecluyse et al., 2019; Vásquez-Urriago et al., 2016). Emerging at the intersection of academia, industry and government, they aim to foster knowledge transfer, support high-tech entrepreneurship, and stimulate regional growth (Albahari et al., 2017; Xie et al., 2018; Sandoval Hamón et al., 2024). Hundreds of STPs have been developed around the globe since becoming a prevalent paradigm of technology and business development (Sandoval Hamón et al., 2024; **IV**). However, there is a growing recognition that the prevalent STP model may be inadequate for addressing the complex challenges we face, from climate change and biodiversity loss to rising inequalities and threats to democracy (**IV**).

This thesis argues that we need to fundamentally rethink the purpose and structure of STPs, and subsequently all of our institutions. Drawing on critical futures studies and polycentric governance, it proposes a more pluralistic vision that moves beyond the focus on high-tech development and profit maximization. Instead, I explore how STPs could embrace and further congeal a cosmolocal framework to become hubs for more democratic, inclusive and sustainable forms of innovation.

Building on investigations of cosmolocal production and the institutional aspect of STPs, this thesis attempts to sketch an alternative near-future landscape through STPs. This vision moves beyond the conventional high-tech, profit-driven model to embrace more polycentric, democratic and sustainable approaches. It aims to illustrate the wider ecosystem of an STP that incorporates desirable and normative dimensions of cosmolocal production. A participatory design approach was employed to create this near-future landscape. Since this representation is inspired within a Western context, it is inherently partial and imperfect, while certain practices and elements discussed may not be universally applicable. However, examining this landscape may bring forth underlying assumptions, values, and expressions of a worldview that could be useful for research and action in other parts of the world (Slaughter, 1997; Slaughter, 2002).

The following near-future landscape (Figure 2) comprises a cosmolocal ecosystem with various interconnected elements that enhance the different technology, business and governance dimensions of STPs. These elements in conjunction with their relevant dimensions do not aim to offer an exhaustive, singular pathway but a more pluralistic configuration that could mitigate present and future challenges. The envisioned cosmolocal STP aims to instigate transformative additions to existing STPs and inspire an alternative approach to the design and implementation of future ones.

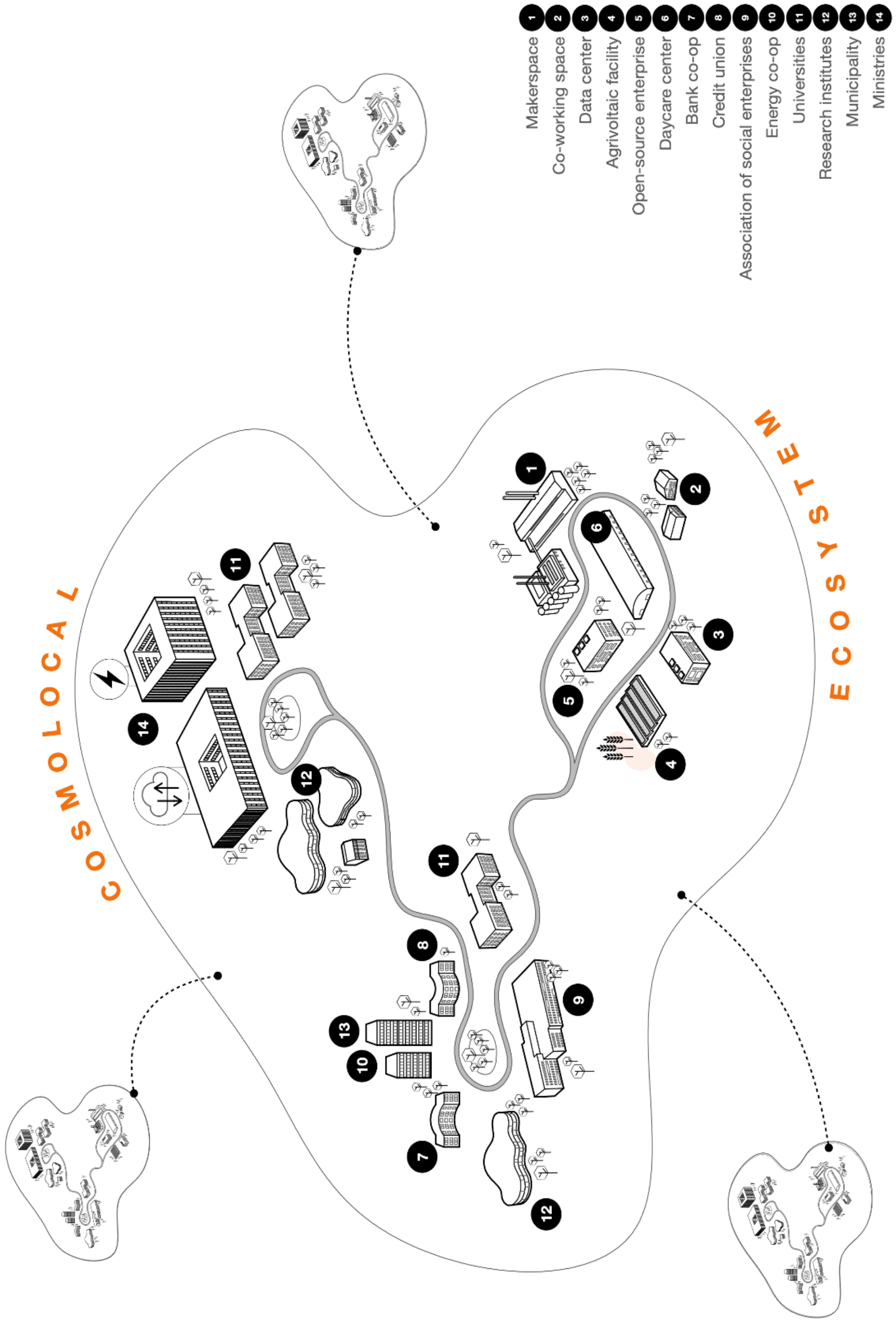


Figure 2. Near-future landscape.

3.1 Elements of the near-future landscape

The elements presented below derive from the four articles comprising this thesis (**I**, **II**, **III**, **IV**) and could carry positive spillovers in an STP context. Similarly to the near-future landscape, the list is partial and imperfect. It can be further enriched and/or modified to more suitably address different needs and conditions.

3.1.1 Open-source enterprises

Open-source enterprises represent an emerging model of organization that challenges conventional business paradigms (Pazaitis & Kostakis, 2022; Robra et al., 2020). They may adopt the form of cooperatives or other organizational structures. These enterprises focus on developing open-source technologies and providing relevant market services. They embody a shift towards more sustainable and democratic approaches to innovation and production (Kostakis et al., 2023a; Robra et al., 2023).

Open-source enterprises emerge from and contribute to digital commons of knowledge, software, and design. They tend to form collaborative networks with other organizations, creating market value around these shared resources while supporting livelihoods for producers of the commons. This approach aligns with the principles of cosmolocal production, combining global knowledge sharing with localized manufacturing (Kostakis et al., 2023a; Troullaki et al., 2022).

In the near-future landscape presented above, open-source enterprises could benefit from the support of shared infrastructures such as makerspaces, co-working spaces, and educational institutions. These spaces could serve as hubs for collaboration, knowledge exchange, and the incubation of new ideas which is integral for the STPs paradigm (Esteves et al., 2021; Lecluyse et al., 2019; **IV**). They facilitate the development and market introduction of open-source innovations, fostering meaningful social relationships and cross-pollination of ideas (Kohtala, 2017; Taylor et al., 2016).

Regarding sustainable technology development, open-source enterprises may focus on producing a broad range of technologies. There are multiple cases to be drawn from fields such as agriculture, energy, prosthetics and space technologies that exemplify the potential of the open-source approach to address pressing socio-environmental challenges (Giotitsas, 2019; Kostakis et al., 2018; **III**).

3.1.2 Makerspace

Makerspaces represent a key element in the envisioned cosmolocal near-future landscape. These shared infrastructures serve as small-scale workspaces offering access to localized manufacturing technologies, including CNC machines, 3D printers, and various tools for crafting and prototyping (Kohtala, 2017; Niaros et al., 2017; **II**, **III**).

Makerspaces have been enablers in community collaboration, knowledge sharing, and localized manufacturing (Kohtala, 2017; Kostakis et al., 2023a; **II**). They could fulfil functions that are crucial for an STP environment, by serving as hubs for diverse stakeholders, including students, researchers, community members, and organizations, to converge and exchange knowledge, develop informal or formal relationships, and collaborate on creating innovative solutions (Poonjan & Tanner, 2020; **IV**).

While makerspaces have not yet reached the scale to rival mass production, they have demonstrated significant potential in empowering individuals and communities to create custom devices tailored to local or personal needs (Kohtala, 2017; Taylor et al., 2016; **II**, **III**). Makerspaces in the envisioned STP ecosystem would support and coordinate a range of activities, from educational workshops to maintenance and repair services (Niaros et al., 2017; **II**, **III**). Additionally, makerspaces within STPs could facilitate the production of various artefacts to be utilized on-site, e.g., a small-scale wind-turbine or an Arduino smart metre (Kostakis et al., 2024a; Troullaki et al., 2022; **III**).

3.1.3 Co-working space

A co-working space is a shared professional environment wherein individuals from diverse backgrounds congregate to fulfil their professional duties. This arrangement facilitates economic efficiency and offers opportunities for formal and informal networking thereby promoting interdisciplinary collaboration and the cross-pollination of ideas (Capdevila, 2015). This workspace setting could be appealing to independent researchers, remote employees and location-flexible professionals. Beyond their physical aspect, co-working spaces enable the cultivation of a collaborative community and creates a sense of collective purpose among its constituents (Mitev et al., 2019).

3.1.4 Credit union and bank co-op

Credit unions and bank co-ops are two examples of cooperative financial institutions. Credit unions are not-for-profit member-owned financial cooperatives that operate democratically with each member having an equal vote, and the membership is usually connected with geographic proximity. What differentiates credit unions from bank co-ops is that the latter are for-profit organizations that provide services to both members and non-members (McKillop et al., 2020). Unlike traditional commercial banks, both cooperative financial models do not seek to maximize profits. They try to bolster and secure local economic resilience by channelling surplus earnings back to members through various strategies, e.g., favorable loan rates and higher savings returns (McKillop et al., 2020). Within the STP ecosystem, these cooperative financial institutions could support startups, social enterprises and other initiatives, while also promoting financial literacy among its members. Additionally, as STPs seek to boost sustainable business development and local economic impact (Ratinho & Henriques, 2010; Xie et al., 2018), credit unions and bank co-ops could play an incremental role towards serving this aim (Fiordelisi & Mare, 2014).

3.1.5 Energy community

STPs tend to host organizations that largely depend on digital technologies and infrastructure (Xie et al., 2018; **IV**). These organizations, due to their high-tech nature, often require energy-intensive processes (Lange et al., 2020). Therefore, to satisfy the large energy demand more sustainably, the envisioned cosmolocal STP could include an energy community. The energy community, or energy co-op, is formed by members who collectively self-produce energy, having substantial ownership and control over their energy resources which embodies the principles of cosmolocal production (Kostakis et al., 2024; **III**).

The energy community operates as a commons, a socio-technical system through which stakeholders collectively manage their shared energy resources (Kostakis et al., 2024a; Ostrom, 1990). In the context of STPs, the cooperative could comprise various stakeholders and interested parties, fulfilling both their energy needs and those of the shared infrastructures. It could include small and medium enterprises, civil society organizations, public buildings, and households. The energy community can produce power through multiple means, depending on local context and conditions, ranging from rooftop solar panels and small-scale water mills to wind turbines, agrivoltaic systems, and biomass facilities.

Beyond energy production, the co-op could engage in energy-saving initiatives, demand-side flexibility and efficiency projects, buildings retrofitting and electric mobility (Kostakis et al., 2024a). To enhance grid flexibility and ensure stability, it could utilize community-owned energy storage systems, facilitate peer-to-peer energy trading, and employ open-source smart energy management systems (Giotitsas et al., 2020; Troullaki et al., 2022).

The energy cooperative model aligns with the principles of energy justice and the goals of STPs in fostering sustainable innovation (Sandoval et al., 2024; **IV**). The emphasis on local, community-owned renewable energy production and democratic governance, energy co-ops can potentially address many of the injustices inherent in conventional, centralized energy systems (Giotitsas et al., 2020).

Within an STP ecosystem, the energy co-op encompasses and collaborates with other elements such as makerspaces and open-source enterprises. This relationship could enable the development and implementation of innovative energy solutions. Also, participation in wider networks of energy cooperatives could create opportunities for knowledge sharing and collective advocacy at national and international levels.

3.1.6 Agrivoltaic facility

The STP's energy co-op could be partially supported by an agrivoltaic facility. Agrivoltaic describes the dual nature that characterizes a plot of land used for both solar energy production and agricultural purposes (Trommsdorff et al., 2021). An agrivoltaic facility opens up many possibilities beyond solely energy production such as food production, establishment of a community garden, livestock feeding and beekeeping. This approach enhances land use efficiency and also demonstrates the potential for integrating renewable energy generation with agricultural activities, addressing multiple sustainability challenges at once.

3.1.7 Universities and other research-related institutions

Universities and other research-related institutions play a crucial role in an STP ecosystem. They serve as centers of innovation, collaboration and knowledge development (Albahari et al., 2017; Link, 2016; Poonjan & Tanner, 2020). The close interconnection of an STP with such institutions potentially creates multiple spillovers for the engaged stakeholders and establishes a mutually favorable relationship (Díez-Vial & Fernández-Olmos, 2015; Vedovello, 1997). Research-related institutions could benefit substantially by collaborating closely with other elements of the STP, such as open-source enterprises and makerspaces, to drive innovation in sustainable technologies and practices. Hence, pursuing not only technical but also socio-technical experiments through a co-creation process with the active engagement of local communities (Trencher et al., 2014; Trencher et al., 2017).

Organizations that cooperate closely with academic and other research institutions are better positioned to benefit from knowledge spillovers, thereby enhancing their innovative capacity (Díez-Vial & Fernández-Olmos, 2015). They develop a mutual understanding which allows stakeholders to more easily identify opportunities and incorporate research-generated knowledge. For instance, entities such as the association of social enterprises or the Open Technologies Alliance, drawn from the Greek context, are included in the cosmolocal near-future landscape because they could serve as nodes for the diffusion of knowledge and enablement of collaborations between stakeholders.

The knowledge transfer occurs not only through formal mechanisms but also through informal encounters and meetings (Poonjan & Tanner, 2020). A complex web of interactions is woven, which enhances a rich ecosystem of knowledge exchange and innovation, benefiting those who actively participate and contribute to this collaborative network.

3.2 Dimensions of the near-future landscape

The dimensions of the near-future landscape touch upon notions that are integral pillars of an STP, i.e., technology, innovation, business, governance and infrastructure (Link & Scott, 2007; McCarthy et al., 2018). It is an attempt to provide a tentative framework that accommodates the inclusion of the elements of the near-future landscape and elaborates on how these elements could prove beneficial in an STP context.

3.2.1 Open-source technologies and convivial innovation

Rather than focusing primarily on proprietary technologies which amplify path dependencies and planned obsolescence, STPs could prioritize the development of open-source hardware and software (**IV**). The open-source model enables collaborative development and free sharing of designs, which could accelerate innovation while keeping technologies accessible and adaptable (Kostakis et al., 2018; **II**, **III**). Technology development strongly resonates with innovation, which dominates public views about growth and future developments (Robra et al., 2023) and is an integral dimension of STPs (Anton-Tejon et al., 2024; Vásquez-Urriago et al., 2016). However, the conventional ‘one size fits all’ approach often followed in STPs has proven ineffective regarding social and environmental sustainability (Albahari et al., 2023; Hobbs et al., 2017; Tödtling & Trippl, 2005).

Research has shown that open-source technologies enhance innovation, empower communities through collaboration, and strengthen local economic and social impact (Hemel & Larrimore Ouellette, 2018; Robra et al., 2023). Examples can be found across diverse fields, including agriculture, building construction, renewable energy, and space technologies (Giotitsas, 2019; **I**, **III**). The benefits of open-source extend beyond technical aspects, influencing business and governance through enhanced conviviality, accessibility, and sustainability (**I**, **II**). However, the transition from proprietary to open-source and localized manufacturing faces significant challenges. Open-source encompasses varying degrees of openness, making it difficult to clearly distinguish between what is truly open-source and what is not. This ambiguity creates vulnerability to openwashing and the risk of co-optation by commercial interests (Bauwens & Jandrić, 2021; Pazaitis & Kostakis, 2022; **II**).

The recognition of open-source technologies has grown substantially across various sectors. Globally renowned media outlets like The Economist and Forbes, but also major consulting corporations such as Deloitte and PricewaterhouseCoopers have acknowledged open-source as a viable alternative to traditional proprietary models (Pazaitis & Kostakis, 2022; **IV**). Enabling humans to regain a degree of agency and control over the technology they are using, allows for a significant part of the production to be localized and achieve an optimal synthesis between the efficiency of high-tech and the resilience of low-tech solutions (Kostakis et al., 2023b; **III**).

By fostering convivial innovation, shared resource management, and local production, STPs could become a beacon towards more sustainable and equitable modes of production in the face of current environmental and socioeconomic crises (Robra et al., 2020; **I**, **II**, **III**). This proposition resonates deeply with multiple elements of the cosmolocal near-future landscape such as the open-source enterprises and the different types of shared infrastructures. For instance, the agrivoltaic facility could serve as a practical demonstration of open-source technologies and convivial innovation within the STP ecosystem. It could provide opportunities for collaborative research, education, and community engagement, further reinforcing the STP's role as a polycentric institution fostering sustainable socio-technical futures through harnessing a pluriverse of alternatives (Demaria et al., 2023; Hemel & Larrimore Ouellette, 2018).

3.2.2 Sustainable business and participatory governance

STPs, influenced by the dominant economic paradigm, have cultivated a monoculture in terms of business development (Hobbs et al., 2017; Laspia et al., 2021; Xie et al., 2018). The cosmolocal near-future landscape suggests a more pluralistic approach could mitigate some challenges while creating opportunities for a more sustainable and inclusive entrepreneurship. To that end, a deep cultural transformation is required, moving away from the notion of business as a profit-maximizing entity and towards the business as a social entity (Nesterova & Buch-Hansen, 2023; Nesterova & Robra, 2022).

STPs, having intrinsically a strong polycentric aspect, comprise a plethora of different stakeholders connected with complex relationships. In the spirit of letting all flowers bloom, an STP could actively support the development of business models that adopt sustainable practices for society and the environment such as social enterprises and cooperatives. While still evolving, such entities focus on resilience, local impact and tend to function more democratically (Pazaitis & Drechsler, 2020; Scholz & Schneider, 2016; **IV**). In the cosmolocal near-future landscape, the various suggested elements, e.g., open-source enterprises, bank co-op, and energy communities, attempt to address burning issues while deploying fairer and more sustainable business practices (Gatto, 2020).

The business side of STPs has significant spillovers also to its governance. Cooperative models tend to adopt participatory governance and organize around social and environmental global issues (Pazaitis et al., 2017). They aim to maximize, not profit, but public value through sharing knowledge and infrastructures (Benkler, 2006; Pazaitis & Drechsler, 2020). Participatory governance is inherent in such entities and, in the context of an STP, it could offer a pathway that mitigates inter- and intra-organizational tensions. Participatory governance permeates all the elements of the near-future landscape, from the management of the shared infrastructures to the interconnection between the multitude of organizations involved in an STP.

The envisioned near-future landscape includes multiple elements which create a welcoming environment and aim to enhance sustainable business and participatory governance. Be it the various co-ops or the governance of shared resources, individuals and communities are urged to be involved in the decision-making as peers, in a less hierarchical manner. Also, through these interactions, the exchange of sustainable business practices and the creation of sustainable business coalitions is facilitated.

3.2.3 Shared infrastructures

Shared infrastructures are physical spaces designed for communal use that play a crucial role in the cosmolocal near-future landscape for STPs. Infrastructures are not merely technical systems but are predominantly social elements that tend to embed deep social needs and interests (Dalakoglou, 2016). These spaces serve multiple functions, acting as meeting points, incubating knowledge exchange, and enabling both formal and informal relationships. By fostering an environment where people from diverse fields and backgrounds come together to create and innovate, shared infrastructures could become the backbone of a vibrant STP ecosystem (Kostakis et al., 2023a; **II**, **IV**).

In the envisioned near-future STP, shared infrastructures could take various forms as depicted in the above-described elements, each serving a specific purpose while contributing to the overall collaborative environment. Other than the makerspace, the co-working space and the agrivoltaic facility described above, an STP could include, for example, a daycare center for the creative engagement of children supporting the work-life balance of individuals. Also, elements such as the bank co-op or the energy community produce a vast amount of data. Therefore, a shared data center could facilitate the storage and management of these data. Not to dismiss of course that data ownership and security are challenging issues that need to be confronted as such by the involved stakeholders. Also, ensuring proper use and maintenance of shared facilities, as well as, the development of an inclusive set of protocols for resource allocation and access could arise as troublesome issues (Kohtala, 2017; Kostakis et al., 2023a; **II**).

The value of these shared infrastructures extends beyond their practical functions. They could significantly impact the resource intensity of technology development processes by mutualising resources and reducing logistics (**I**, **III**). The provision for spaces where diverse stakeholders can interact, experiment, and co-create, can help break down barriers between different disciplines, sectors, and organizations. It is a possible instigator for a more inclusive and resilient approach to technology development and convivial innovation. Shared infrastructures serve as the physical embodiment of the collaborative, open, and sustainable ethos that underpins the cosmolocal approach.

3.2.4 Beyond global versus local

The presented cosmolocal near-future landscape is not confined to the spatial limits of the STP infrastructure. It extends and develops far beyond these limits outlining the contours of an interconnected cosmolocal ecosystem. STPs often adopt an introverted approach, functioning isolated and substantially hindering their local impact and overall effectiveness (da Costa Mineiro et al., 2024; Lecluyse et al., 2019; **IV**).

STPs attempt to address multifaceted, complex problems. The guiding principle of the above-depicted cosmolocal ecosystem is that problems involving multiple levels, e.g., local, regional, national, and global, require contributions to each of these levels (Adler, 2005). To that end, the near-future landscape adopts a polycentric approach and moves beyond the traditional dichotomy of global versus local, acknowledging that while local needs and conditions are integral, they exist within and are influenced by broader networks and systems.

As part of a cosmolocal ecosystem, the STP functions as a nexus, facilitating the flow of knowledge, resources, and innovations across multiple spatial levels. Its boundaries become more fluid and permeable, taking a more distributed, decentralized form. The diverse stakeholders, initiatives, and individuals within the cosmolocal ecosystem engage and communicate, not only within their immediate network but also with similar ecosystems globally (Kostakis et al., 2023a; **III**). A rich tapestry of interactions is enabled, where local solutions can be shared and adapted across different contexts, and global challenges can be mitigated through coordinated local actions. These interactions are crucial for any institution that aims to interact with its extended environment (Parker, 2023).

4 Concluding remarks

This thesis set out to explore how cosmolocal production could be institutionalized to foster sustainable socio-technical futures, through three key lines of inquiry. First, examining the impact of openness and localization principles on sustainability and technology development. Second, investigating supportive institutional arrangements and governance mechanisms. Third, synthesizing these insights to comprehend broader future institutionalization pathways.

The empirical investigations in construction and 3D printing (Articles **I**, **II**) revealed both opportunities and challenges of openness and localization. These principles demonstrated potential for enhancing environmental sustainability through reduced material and energy footprints, enabled by on-demand localized manufacturing and global knowledge sharing. In construction, open-source approaches showed promise for democratizing technology development while incorporating vernacular wisdom. The 3D printing case highlighted how localized manufacturing could reduce supply chain impacts, though dependencies on energy-intensive digital infrastructures remain a challenge.

Regarding institutional arrangements and governance mechanisms (Articles **III**, **IV**), the research identified several key elements needed to support cosmolocal production. These include participatory governance structures, shared infrastructures like makerspaces, and cooperative business models that prioritize social and environmental value over profit maximization. The case study of STPs demonstrated how existing institutions could be reimagined to incorporate these elements, though tensions with dominant economic paradigms persist.

The alternative vision for STPs represents one potential pathway for institutionalizing cosmolocal production. It moves beyond conventional high-tech and profit-maximization focus to embrace more democratic and sustainable approaches to technology development. Key institutional features encompass polycentric governance enabling multiple centers of decision-making, shared infrastructures supporting collaborative production, open knowledge commons fostering innovation, local-global linkages facilitating knowledge exchange while preserving autonomy, and cooperative business models prioritizing sustainability.

However, significant challenges remain. Cosmolocal production continues to depend on energy-intensive infrastructures. Questions of scalability and potential co-optation by dominant economic actors require further investigation. Resource intensity and coordination across scales present ongoing limitations that need to be put under scrutiny.

The research suggests several critical factors for successful institutionalization: building supportive policy frameworks, developing standardized processes while maintaining flexibility for local adaptation, creating sustainable funding mechanisms, fostering cultural shifts toward cooperative approaches, and strengthening connections between diverse initiatives. This thesis thus provides a foundation for understanding how cosmolocal production could be institutionally supported while acknowledging implementation challenges. Future research directions include empirical studies of diverse institutional contexts beyond STPs, investigation of policy and regulatory frameworks to enable cosmolocal scaling, analysis of governance mechanisms across different cultural contexts, and assessment of long-term sustainability impacts.

While acknowledging the difficulties of scaling alternative approaches within dominant capitalist frameworks, the thesis demonstrates that cosmolocal production offers promising glimpses into a more sustainable socio-technical development. Through studying communities actively constructing new paradigms, it provides both theoretical insights and practical guidance for institutional transformation. The research contributes to broader debates about transitions toward sustainable socio-technical systems while offering concrete insights for reimagining institutional frameworks. Though perfect solutions remain elusive, this work illuminates potential pathways forward through careful attention to both opportunities and constraints in fostering more democratic and sustainable modes of production.

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Abstract

Envisioning institutional pathways for cosmolocal production: a near-future landscape through science and technology parks

This thesis examines how an institution, i.e., an STP, could foster cosmolocal production, an emerging configuration of production that combines global knowledge sharing with localized manufacturing to address pressing socio-environmental issues. Following the predominant growth-oriented paradigm, STPs have traditionally served as hubs for high-tech innovation and economic development, but seemingly their conventional approach may be inadequate for addressing complex sustainability challenges. Through the engagement with empirical case studies and theoretical analysis, this thesis investigates how an institution like STPs could be reimagined to embrace more democratic, inclusive, and sustainable approaches to technology development and production.

The thesis employs a qualitative methodological approach across four interconnected articles. It begins with empirical investigations of cosmolocal production in the construction sector and 3D printer supply chains, followed by a theoretical examination of cosmolocal frameworks and their institutional implications. The research culminates in an exploratory case study of a grassroots STP initiative, which informs the development of a near-future landscape for STPs that could foster cosmolocal production.

The main findings suggest that by incorporating various cosmolocal elements and dimensions, STPs could be transformed into collaborative ecosystems for exploring and enabling more sustainable socio-technical futures. The thesis attempts to address various issues that cosmolocal production faces, such as scalability, resource intensity, and potential co-optation by dominant economic actors. Through the investigation of communities actively constructing a new paradigm, this thesis makes a prefigurative attempt to position cosmolocal production in an institutional setting.

The research contributes to ongoing debates about transitions toward more sustainable socio-technical systems and offers practical insights for reimagining institutional frameworks in the face of pressing environmental and social challenges. While acknowledging the difficulties of scaling alternative approaches within dominant capitalist frameworks, the thesis argues that cosmolocal production offers promising pathways for technology development better aligned with sustainability imperatives.

Lühikokkuvõte

Kosmolokaalse tootmise institutsionaalsete teede kavandamine: lähituleviku maastik teadus- ja tehnoloogiaparkide kaudu

See doktoritöö uurib, kuidas institutsioon, st STP, võiks edendada kosmolokaalset tootmist – uut tootmisviisi, mis ühendab globaalse teadmiste jagamise ja kohaliku tootmise, et lahendada pakilisi sotsiaal- ja keskkonnaprobleeme. Valdava kasvule orienteeritud paradigma kohaselt on STP-d olnud traditsiooniliselt kõrgtehnoloogilise innovatsiooni ja majandusarengu sõlmpunktid, kuid nende tavapärane lähenemisviis võib olla ebapiisav keeruliste jätkusuutlikkuse probleemide lahendamiseks. Empiiriliste juhtumiuuringute ja teoreetilise analüüsi abil uuritakse käesolevas väitekirjas, kuidas saaks sellist institutsiooni nagu STP-d ümber kujundada, et võtta kasutusele demokraatlikumad, kaasavamad ja jätkusuutlikumad lähenemisviisid tehnoloogia arendamisele ja tootmisele.

Doktoritöö kasutab kvalitatiivset metodoloogilist lähenemist nelja omavahel seotud artikli kaudu. Alustatakse kosmolokaalse tootmise empiirilise uurimisega ehitussektoris ja 3D-printerite tarneahelates, millele järgneb kosmolokaalsete raamistike ja nende institutsionaalsete mõjude teoreetiline uurimine. Uurimus kulmineerub rohujuure tasandi STP algatuse uuriva juhtumiuuringuga, mis annab teavet STPde lähituleviku maastiku arendamiseks, mis võiks soodustada kosmolokaalset tootmist.

Peamised järeldused viitavad sellele, et erinevaid kosmolokaalseid elemente ja mõõtmeid kaasates võiks STP-d muuta koostöölisteks ökosüsteemideks, et uurida ja võimaldada jätkusuutlikumat sotsiaal-tehnilist tulevikku. Töös püütakse käsitleda erinevaid probleeme, millega kosmolokaalne tootmine seisab silmitsi, nagu mastaapsus, ressursimahukus ja võimalik koopteerumine domineerivate majandusosalejate poolt. Kogukondade uurimise kaudu, kes aktiivselt konstrueerivad uut paradigmat, teeb see töö prefiguratiivse katse paigutada kosmolokaalne tootmine institutsionaalsesse konteksti.

Uurimus aitab kaasa käimasolevatele aruteludele ülemineku üle jätkusuutlikumatele sotsiaal-tehnilistele süsteemidele ja pakub praktilisi teadmisi institutsiooniliste raamistike ümberkujundamiseks, et lahendada pakilisi keskkonna- ja sotsiaalseid probleeme. Tunnistades raskusi, mis kaasnevad alternatiivsete lähenemisviiside laiendamisega domineerivates kapitalistlikes raamistikes, väidab doktoritöö, et kosmolokaalne tootmine pakub paljulubavaid võimalusi tehnoloogia arendamiseks, mis on paremini kooskõlas jätkusuutlikkuse imperatiividega.

Appendix

Publication I

Priavolou, C., **Tsiouris, N.**, Niaros, V., & Kostakis, V. (2021). Towards sustainable construction practices: how to reinvigorate vernacular buildings in the digital era?. *Buildings, 11*(7), 297.

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Article

Towards Sustainable Construction Practices: How to Reinvigorate Vernacular Buildings in the Digital Era?

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Abstract: The starting point of this article is the critique on socioeconomic and environmental implications of conventional construction practices around sustainability. The focus is on exploring the sustainability dynamics of the emerging "Design Global, Manufacture Local" (DGML) configuration with emphasis on building construction. Combined with the concept of conviviality which we identify in aspects of vernacular architecture we explore how it can foster meaningful sustainability practices in the construction sector. We introduce a framework of "open construction systems", an expression of DGML in building construction, as a way to foster the conjunctive use of the digital commons and local manufacturing technologies for the construction of buildings through three interlocked elements—modularity, sharing and adaptability. We suggest that the "open construction systems" framework may point towards more sustainability in building construction.

Keywords: construction; building; commons; sustainability; conviviality

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1. Introduction

There is a wide range of sustainability conceptualisations in the literature. The concept of sustainability was first introduced to indicate a harvesting practice that can be maintained for generations, considering the natural regeneration of forests [1]. It was subsequently used to raise environmental awareness at a global level [2]. Today a mixture of environmental, social, and economic elements exists in the concept of sustainability known as the three pillars of sustainability [3].

In the construction sector, sustainable practices present common values, such as the focus on resource efficiency, social cohesion, and the adoption of cost-effective methods that meet human needs [4]. However, there is no regulatory framework that explicitly states the roles and responsibilities of various stakeholders and clearly describes the process to be followed for a sustainable transition in construction. It has been argued though that sustainability in building construction could thrive through collaborative efforts by the involved stakeholders across the stages of construction [5].

In this article, we posit that conviviality could provide the necessary tools for enhanced sustainability practices in the construction sector. Conviviality is an ethical value that relies on human coexistence and interdependence for wellbeing [6]. In contrast with a convivial approach, the pursuit of growth-oriented approaches "defuturises" the future, meaning that the future is deprived of part of its potential [7,8]. In addition, these approaches may negatively impact people, causing mental health issues or undermining morality [9,10].

We identify a strong presence of conviviality in vernacular buildings. Vernacular architecture refers to a modest style of building that relies on the use of local resources and knowledge to construct buildings. Vernacular buildings constitute exemplifications of how conviviality can be deployed in the construction sector and provide multiple benefits to the three pillars of sustainability.

Furthermore, we draw inspiration from an emerging production configuration based on the digital commons, which is codified as Design Global, Manufacture Local (DGML) [11]. Building on DGML in conjunction with the conviviality present in vernacular architecture, we introduce Open Construction Systems (OCSs), which expand the focus of attention from the building structure to the ecosystem around it, required to enable the lifecycle management of buildings. The questions that have acted as a trigger for this article are: How could vernacular buildings evolve in tandem with current technological regimes to provide local responses to the global pressing need for sustainability in building construction? Could OCSs provide a solution towards that direction?

Looking towards fostering sustainability, we argue that OCSs could inaugurate a conviviality-inspired sustainable pathway in building construction by reinvigorating vernacular architecture and reinforcing it with technological capacities [7,12]. In other words, it borrows elements from both contemporary digital tools used in the construction and the tacit knowledge found in vernacular practices still employed in developing regions of the planet. We hence elaborate on three interlocked elements for conviviality observed in the development of OCSs using the Matrix of Convivial Technology [13]. We also discuss the potential benefits these elements could have on the construction sector.

The remaining part of this article is organised as follows. Section 2 discusses sustainability-related issues in the construction sector, introduces the DGML configuration and indicates how conviviality could boost sustainability practices in buildings as exemplified through vernacular architecture. Section 3 describes the framework of OCSs, elaborating on how core elements of OCSs could enhance conviviality in building construction and we discuss the positive impact this may have towards sustainability. Finally, Section 4 summarises our insights.

2. Shifting towards Sustainability in Building Construction

2.1. *Sustainability in Conventional Construction Practices*

In the context of the conventional construction practices, a producer–consumer relationship has been established that restricts the engagement of individuals in the construction process, infringing on the human right to housing [14,15]. Further, high rates of gender discrimination, corruption, and labour-intensive activities have been observed in building construction, while the quality performance of buildings is usually disregarded in pursuit of maximising economic gains [16]. In addition, detrimental environmental effects of the construction sector cannot be overlooked, considering that building construction accounts for 39% of global carbon emissions [17,18].

Despite the identification of these issues, construction practices have barely changed during the last six decades [19–21]. The need to implement sustainable practices in building construction has only recently attracted attention [22]. Although there is not yet a unified framework for sustainable construction, it has been strongly posited that multidimensional and collaborative approaches should be implemented to achieve a shared vision on sustainable construction [5]. Towards that goal we believe that the elements of OCSs enabled through the DGML configuration could play a key role in addressing several of the aforementioned issues.

2.2. *Introducing the Design Global, Manufacture Local Configuration*

Information and Communication Technologies (ICTs) have facilitated the development of digital platforms that favour online information sharing. Given the potential of these platforms to enhance collaboration and knowledge transfer at low costs, ICTs have been portrayed as a booster of democratisation [23,24]. Immaterial resources (such as knowledge, software, and designs) can be distributed through the Internet and shared around the globe as a “digital commons” [25] “Digital commons” can be utilised to provide local solutions, bearing in mind surrounding biophysical conditions [11].

At the same time, local manufacturing technologies (i.e., 3D printers and laser cutters) enable the production of objects locally, thus facilitating distributed production networks with significant societal impacts [26]. The distribution of these technologies boosts creativity and experimentation, offering opportunities for transitions towards sustainability and peer-to-peer ways of producing artefacts [27]. The development of open source hardware solutions (for example the Arduino microcontroller board (https://www.arduino.cc/en/guide/introduction. Accessed on 6 July 2021) and Open Bionic Systems (https://openbionics.org/. Accessed on 6 July 2021) exemplifies how the manufacturing process of physical products can be transformed through collaborative efforts [11].

The convergence of global "digital commons" with local manufacturing technologies has been outlined through the DGML configuration. DGML differs from the conventional market-driven production one in its promotion of distributed production realised in local but networked makerspaces [11,28]. The collective intelligence and cooperation embedded in the development of DGML solutions strengthen the potential of relevant initiatives to foster innovation [29]. Information behind the development process of technological solutions is shared as a "digital commons", which can undergo asynchronous modifications by contributors.

DGML communities produce technological solutions locally on-demand through sharing both digital and physical infrastructure. Further, they purposely design products to last, focusing on social wellbeing while moving away from profit maximisation-oriented practices [30]. The primary motives of commons-based communities stem from their need for communication, learning, and emotional fulfilment [23], aligning with values like sociability and self-development embedded in convivial processes. Besides, research has illustrated interrelated practices observed in the development of DGML products that create positive feedback loops towards conviviality [11]. Thus, it can be posited that DGML practices could foster the human-centric shaping of technology.

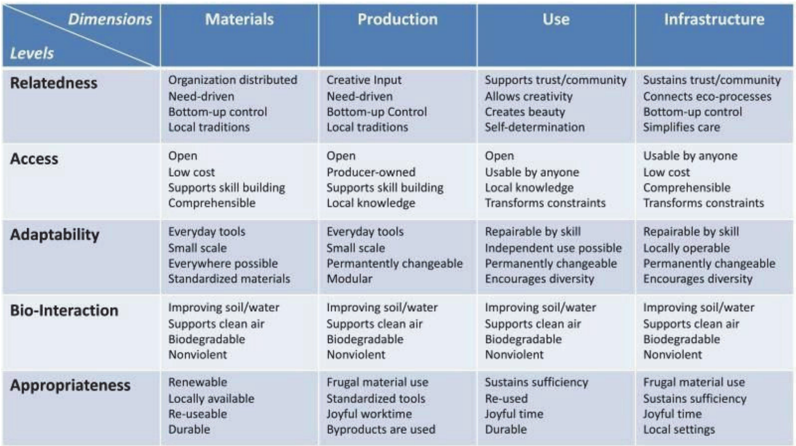
2.3. A Conviviality-Based Sustainability

Echoing [6], conviviality is an intrinsic ethical value that correlates with "individual freedom realised in personal interdependence". "Survival, justice and self-defined work" are basic ideals of conviviality [6] that summarise key values included in the concept of sustainable development [31]. The social pillar of sustainability is associated with human wellbeing and includes a large list of issues related to education, social inclusion, health, safety, housing, employment and more [32]. In a convivial setting, the broader public is involved in the decision-making and production processes. Hence, human needs are taken into account, while perceptions around wellbeing can be redefined and configured collectively [7].

Pursuing a path to conviviality is not easy. There is a need to transform existing production and consumption models, as advocated by the degrowth movement [33]. The idea is to prioritise the assimilation of conviviality ideals in daily life instead of merely enhancing efficiency and optimising performance to achieve sustainability [34]. Besides, the use of energy-efficient systems does not necessarily mean that less consumption takes place if consumption patterns remain unchanged [35].

Convivial technologies are designed in such a way that users can learn about the technology and modify it according to their needs, without the necessity of relying on specialists [36]. They are decentralised, reversible, and democratically controllable [37]. Decentralisation takes place through the implementation of small-scale production units that create distributed supply chains by using local resources [28]. Reversibility is enhanced when the "black-box" behind the development process of products opens up to the public, enabling the transparency of information and inclusion of users in the production of artefacts [38]. By keeping technologies under democratic control, groups of individuals can produce technologies in a collaborative manner to cover their own needs [6].

Conviviality is a broad and abstract concept. In order to provide an accessible and comprehensive means of assessing the degree of creativity, autonomy, and decentralisation in community-based practices, the Matrix of Convivial Technology (MCT) has been developed [13]. As an empirical tool, the MCT allows participants in technological development processes to examine certain conviviality elements on a case-by-case basis (see Appendix A). As depicted in Figure 1, different levels connected to the impact of technology on human relations (relatedness), the adaptability of technology to local contexts, accessibility to technological means, the bio-interaction of technology with the environment, and the appropriateness of socio-ecological benefits of technology in relation to its socioecological impact are examined.



Dimensions *Levels*	**Materials**	**Production**	**Use**	**Infrastructure**
Relatedness	Organization distributed Need-driven Bottom-up control Local traditions	Creative Input Need-driven Bottom-up Control Local traditions	Supports trust/community Allows creativity Creates beauty Self-determination	Sustains trust/community Connects eco-processes Bottom-up control Simplifies care
Access	Open Low cost Supports skill building Comprehensible	Open Producer-owned Supports skill building Local knowledge	Open Usable by anyone Local knowledge Transforms constraints	Usable by anyone Low cost Comprehensible Transforms constraints
Adaptability	Everyday tools Small scale Everywhere possible Standardized materials	Everyday tools Small scale Permantently changeable Modular	Repairable by skill Independent use possible Permanently changeable Encourages diversity	Repairable by skill Locally operable Permanently changeable Encourages diversity
Bio-Interaction	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent
Appropriateness	Renewable Locally available Re-useable Durable	Frugal material use Standardized tools Joyful worktime Byproducts are used	Sustains sufficiency Re-used Joyful time Durable	Frugal material use Sustains sufficiency Joyful time Local settings

Figure 1. Dimensions and levels of the MCT. Adapted by: https://www.andrereichel.de/2019/05/20/artificial-intelligence-convivial-technology/. Accessed on 6 July 2021.

Contemporary tools for assessing the life cycle sustainability impact of products, such as environmental Life Cycle Assessment and Life Cycle Sustainability Assessment methods, tend to focus on a specific pillar of sustainability (i.e., environmental, social, economic). In that sense, the MCT could broaden our understanding of the complexity entailed in systems and social relations [39] by incorporating social, environmental, economic but also cultural and political elements towards comprehensive sustainability assessments.

The reconciliation of environmental, social, economic, spatial, and cultural demands in the construction process is essential for sustainable practices. Vernacular buildings exemplify how the reconciliation of natural elements and building components is possible. Such buildings are made of materials, such as stone, wood, mud, and straw that come from the nearby environment and undergo minimal processing. Natural resources (such as the soil, sun, vegetation, and wind) are used to fulfil to some extent the energy demands for cooling, heating, and lighting. Hence, harmonious interactions between the building, climate, and natural environment are fostered, following the principles of biophilic design [40]. These principles enhance energy saving, economic efficiency, environmental gains, and the improvement of indoor living conditions.

The construction of vernacular buildings is founded on intrinsically convivial construction principles, given the use of local resources to meet economic and natural limitations and the collaborative construction processes involved in relevant practices. More specifically, the region-specific nature of vernacular buildings is evident since local elements, like customs, religions, climate, and topography, are considered [41]. Despite local variations, vernacular buildings share common principles [42], including the utilisation of natural specificities (such as raw materials and energy sources) and the accrued knowledge of communities. This knowledge is empirically gained from observations of the natural environment and experimentations with local construction materials and techniques, enabling communities to build structures collaboratively and intuitively, while the need for professionals is usually minimised [43,44]. In the next section, we introduce the OCSs framework as a tool that could enable a conviviality-based sustainability in building construction.

3. Open Construction Systems as a Convivial Framework for Building Construction

In the light of the pressing need for sustainable practices in the construction sector, we discuss how a sustainable paradigm in buildings could take place using conviviality as a core tenet. We build on existing research around the exploration of DGML solutions from a degrowth perspective with emphasis on conviviality [11,45], illuminating a DGML-based framework in building construction that incorporates vernacular architecture but also relies on contemporary technologies. To this end, we explore the conviviality dynamics of OCSs, which have been studied from multifaceted aspects, ranging from their technological dynamics [46,47] to their socioinstitutional potential [46,48]. To narrow down the ambiguity entailed in the concept of conviviality [49], the MCT is used as a normative schema to provide insights on how OCSs could enhance conviviality in building construction.

3.1. Conceptual Framework of Open Construction Systems

In this subsection, we employ the conceptual framework of the DGML configuration l to delineate the contours of commons-based practices in building construction, albeit in a seed form [46,48]. We unravel the conditions under which such practices could thrive utilising the core principle of conviviality. In this vein, we aspire to prefigure alternative meaningful practices in building construction [50].

We use the term OCSs to delineate a set of connected “things” and “devices” that operate together in designing globally and manufacturing locally buildings. This set may include i. equipment (such as parametric design tools and local manufacturing technologies), ii. information resources (such information related to the digital commons and vernacular architecture), iii. community practices (such as the ones implemented in makerspaces or by open source communities), and iv. legal components (such as public copyright licences and building regulations).

Open Building Systems (OBSs) are the starting point of OCSs. The term OBSs was introduced to describe modular building components able to form a variety of building types [51,52]. OBSs are based on structured components that allow for interchangeability and present a certain degree of customisation and flexibility. The concept of OCSs expands the focus of attention from the building structure to the necessary ecosystem for fostering the lifecycle management of OBSs. Initiatives like the Hexayurt, the Open Source Ecology Microhouse, and the WikiHouse exemplify emerging forms of OCSs [46]. Figure 2 represents the conceptual framework of OCSs.

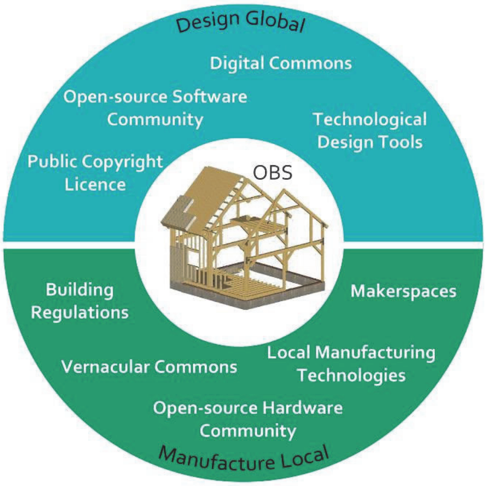


Figure 2. Conceptual framework of OCSs.

OCSs prefigure niche practices that take place on the margins of the dominant paradigm through community-based processes. They question the conventional construction model by inaugurating a new organisational and production framework that moves away from market-regulated structures. Given that issues like environmental concerns, social exclusion, and labour-intensive activities in building construction are common to all contexts, communities involved in the development of OCSs share common values and principles, which promote collaboration and bonding among the communities, and attempt to actively address the aforementioned issues.

However, beyond such shared focus of OCSs, a combination of cultural, economic, social, and techno-political specificities shapes the goals, interests, actions, and structure of OCSs locally. Each of these community-driven initiatives has its own goals, ranging from providing disaster relief shelters (like the Hexayurt initiative) to developing high-performance and affordable buildings (like the WikiHouse initiative). By providing a framework for OCSs, we want to urge engineers and social scientists to visualise common paths towards sustainable construction practices, bringing humanity and conviviality into focus [53]. Our ultimate goal is to highlight the capacity of OCSs to advance societal transformation and rouse meaningful processes of social change.

3.2. Three Interlocked Elements for Conviviality

In this section, we elaborate on three interrelated elements, i.e., modularity, sharing, and adaptability, observed in OCSs that seem to create positive feedback loops for conviviality, which respectively enhances sustainability. More specifically, modularity enables the decomposition and recombination of building modules, simplifying structures and increasing inclusiveness in the construction process [54] Sharing allows for the mutual benefit of individuals from the same resources and enables the production of collective value and shared purpose [55]. Adaptability is catalysed through the engagement of users in the construction process and is enabled via modularity and sharing [56].

Coming back to the five substantial features of convivial technologies that correspond to the levels of the MCT, a correlation between the five levels of the MCT and the three elements for conviviality can be made. In that sense, modularity potentially facilitates accessibility to technology (access) considering its capability to simplify complex solutions; sharing strengthens socioecological relations (relatedness, biointeraction, and appropriateness) through the promotion of bonding among the community itself and the community with the environment; adaptability facilitates the consideration of local contexts in the production of buildings. Figure 3 depicts the main conviviality features observed in OCSs, which are analysed below.

3.2.1. Modularity

Modularity refers to the property of structures to be easily decomposed and recombined in smaller parts—modules [54]. It provides a useful means to deal with complex systems and customise solutions [57,58]. Given the high complexity levels and interdependence among various stakeholders involved in building construction, modularity is important for handling the complexity of building systems. By increasing the modularity of building systems, certain processes can be structured and design decisions can be decoupled [59].

Modularity is embedded both in the design tools used but also in the structure of OBSs. During the design process of buildings, parametric design tools such as BIM technology enable the decomposability of buildings into distinct modular but interrelated components, which function independently to enhance computational analyses of buildings. Although parametric tools in principle allow for infinite modifications in the form and shape of components, fixed rules apply so that BIM software can grasp internal relationships between building components. These rules impose restrictions on the accurate design of certain elements of vernacular buildings since standardised building components are used to form structures and superstructures [60].

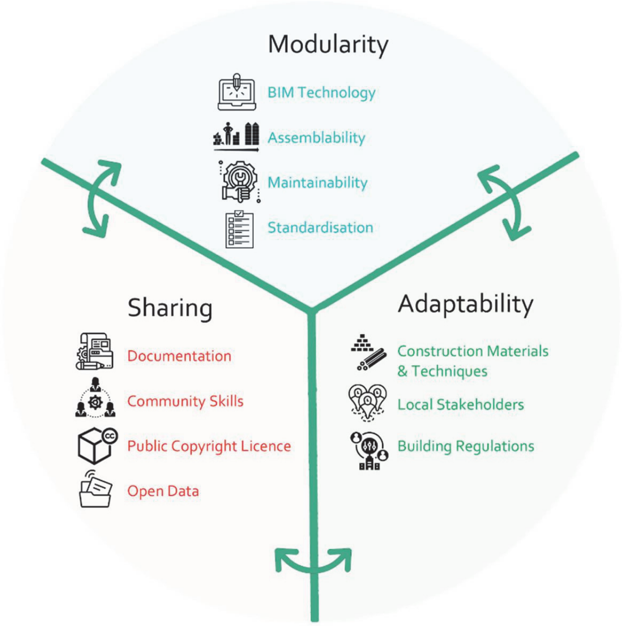


Figure 3. Conviviality features of OCSs.

Thus, the structuring of building information enabled through BIM technology creates both a challenge and an opportunity. The challenge is related to the need for explicitly defined rules that may obstruct the imprint of distinctive building components [47]. The opportunity correlates with the capability to replicate building solutions by codifying and sharing parameterised objects. Such a potential empowers BIM technology to provide a precise interface with an integrated set of applications for well-defined modular building types, like the WikiHouse.

The design-embedded modularity in OBSs facilitates the construction, maintenance, and disposal of OBSs. For example, a WikiHouse structure includes the structural framework (chassis), the electrical equipment, the foundation, the mechanical equipment, the roof, and solar utilities. With the aid of modularity, all these subsystems can be constructed asynchronously and the surrounding community can participate depending on ability and interests to undertake specific parts of the construction process. Additionally, certain tasks can be outsourced to expedite but also simplify the entire process [54]. Modularity hence leads to a division of human labour that reduces the overall complexity of the construction process and makes the entire process more accessible and inclusive. It offers the flexibility to independently piece together, modify, rearrange, repair, and substitute modules so that the needs of users are best suited. Thus, modularity strengthens social interactions and community building, which are crucial for a more sustainable future.

3.2.2. Sharing

Sharing and collaboration are fundamental for all stages of the construction process of OCSs. Sharing takes place both in distributed makerspaces, where equipment and simple tools are used by local communities, but also online, given that digital resources are utilised for the production of open source building solutions. Collaborative processes are evident throughout the construction stage of OCSs, where subgroups work asynchronously on the assembly process of different parts, developing friendship and joyful feelings [48]. Shared resources are managed by communities, which set the rules for using resources in a fairer manner for all, with an eye to optimising production while minimising the processing of material. Recyclable, locally sourced, and reused materials are preferred to mitigate environmental impacts.

The existence of detailed documentation guides/manuals facilitates the replicability and openness of OCSs [61]. Architectural data, construction details, as well as chemical, environmental, economic, and biophysical information should be extensively documented to foster autonomy during the construction and maintenance phases of OBSs. Additionally, by accessing international codified datasets of vernacular architecture and disseminating construction practices of various districts, experimentation and combinations of best practices could be fostered, spreading the impact of local commons-based initiatives. Nevertheless, in the current stage of OCSs, fragmentation issues arise due to the lack of a comprehensive platform that includes all the up-to-date information around them. For instance, in the case of the WikiHouse, uncategorised and non-engineered design files are usually shared on online platforms, like GitHub. Besides, the existence of a complete bill of materials for OCSs is challenging considering the context-dependent nature of buildings [48].

Additionally, the plurality of expertise and skills among the participants in the construction process enhances autotomy during the construction and maintenance stages of OBSs. The level of conviviality in the construction phase rises when a highly engaged community with a strong supporting network is involved. However, in the current stage of OCSs, concerns have been raised regarding the ability of users to maintain certain building infrastructures, such as plumbing and electricity modules [48]. Technical interventions are hence necessary at certain stages which indicates that OCSs still have a long way to go.

Concerning the legal framework required, Creative Commons public copyright licences enable the free distribution of building solutions facilitating the integration of the construction industry. Such a condition empowers broad participation in the research and development of OCSs by providing technical support to local communities throughout the building supply chain.

Raising awareness about the importance of scaling up the impact of OCSs for humanity is significant to foster conviviality through the engagement of individuals in relevant processes. Some steps to this direction could be made through the orientation of science and education towards open data, the promotion of open source technologies by policymakers, and the integration of open source structured protocols for data sharing and coordination among stakeholders: from local governments and professionals to international organisations. Such protocols could set the ground for the effective implementation of construction practices in each region and country and the establishment of networks and partnerships at regional, national, and international levels. Moreover, the physical infrastructure needed for the development of OCSs should be provided, including the creation of physical co-working spaces and distributed ad hoc divisions for consultancy on administrative procedures at a national level.

3.2.3. Adaptability

The international homogenisation of building structures taking place through unsustainable construction practices has indicated the need for adaptability to local contexts with an eye to biophysical conditions [62]. The emphasis of OCSs is placed on endorsing adaptability according to human needs rather than offering one-size-fits-all solutions. Following, we elaborate on the ways adaptability could enhance conviviality and help form a more sustainable construction sector.

During the introduction of OBSs, monolithic and standardised materials are usually used as a starting point to facilitate experimentations with OBSs. For instance, standardised sheets of plywood are used for the construction of the WikiHouse chassis system usually obtained from Finnish wood industry producers. As the pool of digital commons for OCSs grows, new materials and designs are being tested in local contexts to enhance the performance of buildings through the use of sustainable materials and techniques. The use of open data could democratise accessibility to material-related properties and performance data. In this direction, platforms, like Materiom (https://materiom.org/. Accessed on 6 July 2021), can provide recipes for materials made from natural and bio-based ingredients, including agricultural waste. In that sense, open source databases could further decentralise the production of OCSs by providing the means needed to self-produce construction materials.

Distributed networks of local stakeholders (architects, manufacturers, designers, structural engineers) could provide technical support to end users and modify digital resources based on regional specificities. OBSs bear an inherent potential for adaptability to local building regulations owing to their design-embedded modularity that enables modification of building components to fit predefined geometric constraints. The development of open databases with regulation-related documents and the simplification of international technical guidelines could enhance the reproducibility of OCSs at local levels [63]. Finally, using smart features and geospatial technologies, certain types of OBSs, building regulations, available construction materials, and administrative processes could be pointed to on a context-specific basis.

4. Conclusions

Despite the plurality of existing perspectives towards sustainable construction, the challenge still remains unanswered. To provide preliminary answers to sustainable practices in building construction, we explore an alternative production model, the DGML configuration that brings the social elements of sharing and solidarity into focus. We stress the importance of introducing conviviality elements in building construction, which could foster a meaningful sustainability paradigm. In this regard, we delineate the contours of DGML in building construction through the concept of OCSs, illustrating the positive dynamics for conviviality. Hence, we identify three interlocked elements for conviviality in OCSs: design-embedded modularity, sharing practices of digital and physical infrastructures, and adaptability to local contexts.

Though our analysis, we conclude that OCSs present non-negligible tendencies towards a conviviality-based sustainability. We also formulate proposals to boost the conviviality potential of OCSs, such as advancements in Building Information Modelling technology; the implementation of open source protocols for data sharing; the institutionalisation of open source communities; as well as the integration of existing open source platforms to facilitate accessibility to building information.

Considering the involvement of diverse stakeholders, including professionals and governmental organisations (i.e., central government, local authorities, etc.) in the construction processes, the above-mentioned issues cannot be addressed in the absence of cooperation across stakeholders and institutional transformations. By stimulating policy-making efforts to build relevant institutions, OCSs could pave the way for an inclusive and democratic approach in the construction sector. To enable the flourishing of OCSs at regional, national, and global levels, awareness should be raised about the socioenvironmental considerations in the construction sector.

A point of criticism one may level against this article is the lack of empirical data regarding the maintenance and disposal stages of OCSs, which is due to the seed form of OCSs. We invite future research to focus on evidence-based assessments for these stages to provide sound data about the lifecycle performance of OCSs. A comprehensive sustainability comparison of an industrially produced building with a similar OBS would also be beneficial. For that purpose, a compilation of targeted and structured tools should be used to assess both the building structure and the ecosystem around it. The development and institutionalisation of such tools could foster meaningful sustainability assessments in building construction, facilitating the investigation of OCSs developed in different socioeconomic contexts.

Lessons should be drawn from global experiences and effective strategies should be developed on local levels, bearing in mind regional social, economic, and political specificities. Vernacular architecture can be a useful asset for defining principles for sustainable design at local contexts, while offering the opportunity to digest and assimilate conviviality values. Such values could enable us to build a common future with a particular focus on human interrelation and wellbeing. In that sense, we do not expect self-construction usually observed in vernacular practices to become a dominant construction practice. Our proposition is that certain elements of vernacular architecture, within the DGML configuration, could be utilised to point the way towards a more sustainable building sector. We thus believe that OCSs could introduce a promising pathway for fostering convivial practices in building construction by reinvigorating vernacular buildings. This could potentially mobilise individuals to acquire a more active role in building construction. The question, however, of whether we want to follow a promising but arduous path towards a sustainable future remains; and the answer is up to us.

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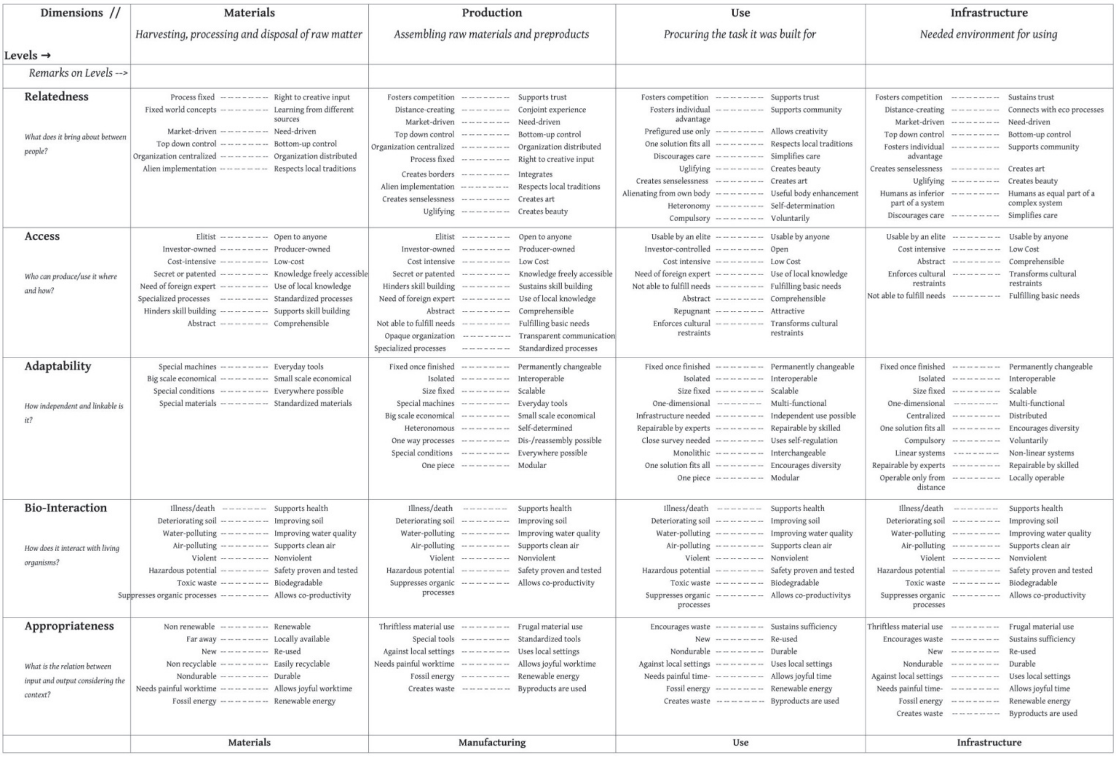
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The Matrix of Convivial Technology by Vetter (2018).



Dimensions // **Levels →**	**Materials** *Harvesting, processing and disposal of raw matter*	**Production** *Assembling raw materials and preproducts*	**Use** *Procuring the task it was built for*	**Infrastructure** *Needed environment for using*
Remarks on Levels -->				
Relatedness *What does it bring about between people?*	Process fixed ---------- Right to creative input Fixed world concepts ---------- Learning from different sources Market-driven ---------- Need-driven Top down control ---------- Bottom-up control Organization centralized ---------- Organization distributed Alien implementation ---------- Respects local traditions	Fosters competition ---------- Supports trust Distance-creating ---------- Conjoint experience Market-driven ---------- Need-driven Top down control ---------- Bottom-up control Organization centralized ---------- Organization distributed Process fixed ---------- Right to creative input Creates borders ---------- Integrates Alien implementation ---------- Respects local traditions Creates senselessness ---------- Creates art Uglifying ---------- Creates beauty	Fosters competition ---------- Supports trust Fosters individual advantage ---------- Supports community Prefigured use only ---------- Allows creativity One solution fits all ---------- Respects local traditions Discourages care ---------- Simplifies care Uglifying ---------- Creates beauty Creates senselessness ---------- Creates art Alienating from own body ---------- Useful body enhancement Heteronomy ---------- Self-determination Compulsory ---------- Voluntarily	Fosters competition ---------- Sustains trust Distance-creating ---------- Connects with eco processes Market-driven ---------- Need-driven Top down control ---------- Bottom-up control Fosters individual advantage ---------- Supports community Creates senselessness ---------- Creates art Uglifying ---------- Creates beauty Humans as inferior part of a system ---------- Humans as equal part of a complex system Discourages care ---------- Simplifies care
Access *Who can produce/use it where and how?*	Elitist ---------- Open to anyone Investor-owned ---------- Producer-owned Cost-intensive ---------- Low-cost Secret or patented ---------- Knowledge freely accessible Need of foreign expert ---------- Use of local knowledge Specialized processes ---------- Standardized processes Hinders skill building ---------- Supports skill building Abstract ---------- Comprehensible	Elitist ---------- Open to anyone Investor-owned ---------- Producer-owned Cost intensive ---------- Low Cost Secret or patented ---------- Knowledge freely accessible Hinders skill building ---------- Sustains skill building Need of foreign expert ---------- Use of local knowledge Abstract ---------- Comprehensible Not able to fulfill needs ---------- Fulfilling basic needs Opaque organization ---------- Transparent communication Specialized processes ---------- Standardized processes	Usable by an elite ---------- Usable by anyone Investor-controlled ---------- Open Cost intensive ---------- Low Cost Need of foreign expert ---------- Use of local knowledge Not able to fulfill needs ---------- Fulfilling basic needs Abstract ---------- Comprehensible Repugnant ---------- Attractive Enforces cultural restraints ---------- Transforms cultural restraints	Usable by an elite ---------- Usable by anyone Cost intensive ---------- Low Cost Abstract ---------- Comprehensible Enforces cultural restraints ---------- Transforms cultural restraints Not able to fulfill needs ---------- Fulfilling basic needs
Adaptability *How independent and linkable is it?*	Special machines ---------- Everyday tools Big scale economical ---------- Small scale economical Special conditions ---------- Everywhere possible Special materials ---------- Standardized materials	Fixed once finished ---------- Permanently changeable Isolated ---------- Interoperable Size fixed ---------- Scalable Special machines ---------- Everyday tools Big scale economical ---------- Small scale economical Heteronomous ---------- Self-determined One way processes ---------- Dis-/reassembly possible Special conditions ---------- Everywhere possible One piece ---------- Modular	Fixed once finished ---------- Permanently changeable Isolated ---------- Interoperable Size fixed ---------- Scalable One-dimensional ---------- Multi-functional Infrastructure needed ---------- Independent use possible Repairable by experts ---------- Repairable by skilled Close survey needed ---------- Uses self-regulation Monolithic ---------- Interchangeable One solution fits all ---------- Encourages diversity One piece ---------- Modular	Fixed once finished ---------- Permanently changeable Isolated ---------- Interoperable Size fixed ---------- Scalable One-dimensional ---------- Multi-functional Centralized ---------- Distributed One solution fits all ---------- Encourages diversity Compulsory ---------- Voluntarily Linear systems ---------- Non-linear systems Repairable by experts ---------- Repairable by skilled Operable only from distance ---------- Locally operable
Bio-Interaction *How does it interact with living organisms?*	Illness/death ---------- Supports health Deteriorating soil ---------- Improving soil Water-polluting ---------- Improving water quality Air-polluting ---------- Supports clean air Violent ---------- Nonviolent Hazardous potential ---------- Safety proven and tested Toxic waste ---------- Biodegradable Suppresses organic processes ---------- Allows co-productivity	Illness/death ---------- Supports health Deteriorating soil ---------- Improving soil Water-polluting ---------- Improving water quality Air-polluting ---------- Supports clean air Violent ---------- Nonviolent Hazardous potential ---------- Safety proven and tested Suppresses organic processes ---------- Allows co-productivity	Illness/death ---------- Supports health Deteriorating soil ---------- Improving soil Water-polluting ---------- Improving water quality Air-polluting ---------- Supports clean air Violent ---------- Nonviolent Hazardous potential ---------- Safety proven and tested Toxic waste ---------- Biodegradable Suppresses organic processes ---------- Allows co-productivitys	Illness/death ---------- Supports health Deteriorating soil ---------- Improving soil Water-polluting ---------- Improving water quality Air-polluting ---------- Supports clean air Violent ---------- Nonviolent Hazardous potential ---------- Safety proven and tested Toxic waste ---------- Biodegradable Suppresses organic processes ---------- Allows co-productivity
Appropriateness *What is the relation between input and output considering the context?*	Non renewable ---------- Renewable Far away ---------- Locally available New ---------- Re-used Non recyclable ---------- Easily recyclable Nondurable ---------- Durable Needs painful worktime ---------- Allows joyful worktime Fossil energy ---------- Renewable energy	Thriftless material use ---------- Frugal material use Special tools ---------- Standardized tools Against local settings ---------- Uses local settings Needs painful worktime ---------- Allows joyful worktime Fossil energy ---------- Renewable energy Creates waste ---------- Byproducts are used	Encourages waste ---------- Sustains sufficiency New ---------- Re-used Nondurable ---------- Durable Against local settings ---------- Uses local settings Needs painful time- ---------- Allows joyful time Fossil energy ---------- Renewable energy Creates waste ---------- Byproducts are used	Thriftless material use ---------- Frugal material use Encourages waste ---------- Sustains sufficiency New ---------- Re-used Nondurable ---------- Durable Against local settings ---------- Uses local settings Needs painful time- ---------- Allows joyful time Fossil energy ---------- Renewable energy Creates waste ---------- Byproducts are used
	Materials	**Manufacturing**	**Use**	**Infrastructure**

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

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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.

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 et al. (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

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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., 2015a; 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., 2015b). 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 a, b), 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., 2018). 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 a, b, 2018) 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., 2015b). 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., 2018). 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., 2018), 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 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 end of life 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., 2015a; 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, 2019; 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.

The methodological steps of our study are summarised in Fig. 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.

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

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

Model | User	Production elements associated with DGML			
	Openness (design)		Localisation (manufacturing)	
	Open licence	Open documentation	Local assembly	Capacity for local manufacturing
Makerbot Replicator+ | Org. A				
Makerbot Replicator Mini | Org. B				
Cubex Duo | Org. A				
Ultimaker 2 | Org. C	X			
Lulzbot Taz 6 | Org. D	X		X	
Ultimaker Original | Org. C	X		X	
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)

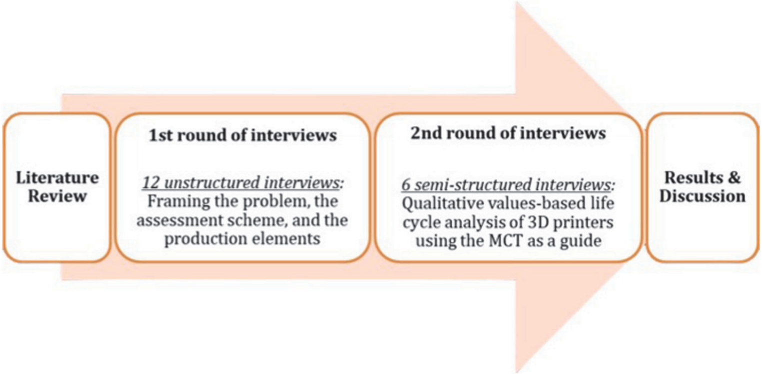


Fig. 1. Methodological steps followed during the research process.

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 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 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.

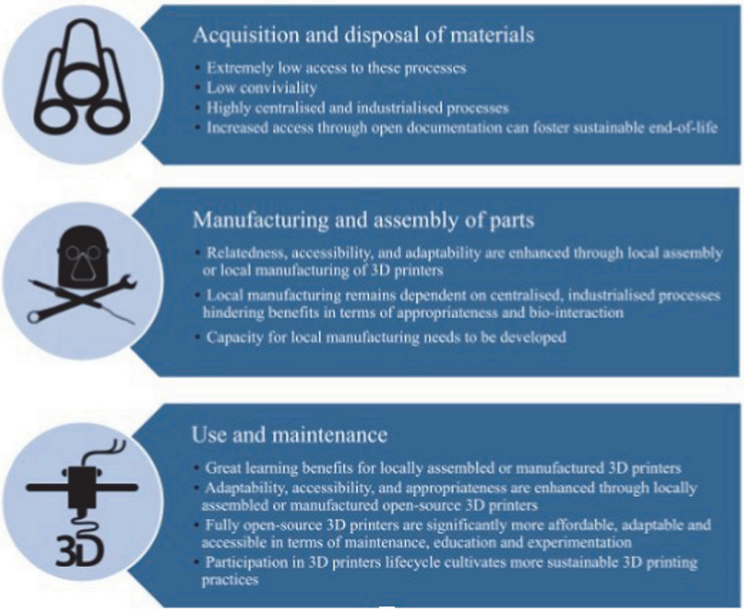
In general, the interviewees did not consider 3D printers as a technology that benefits the environment; unless filament produced from recycled plastic is used. They were greatly interested in addressing ecological issues related to the operation of 3D printers, including the use of recyclable materials 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 Fig. 2, our findings for the three stages of the 3D printer life cycle are summarised.

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-



Acquisition and disposal of materials

- Extremely low access to these processes
- Low conviviality
- Highly centralised and industrialised processes
- Increased access through open documentation can foster sustainable end-of-life

Manufacturing and assembly of parts

- Relatedness, accessibility, and adaptability are enhanced through local assembly or local manufacturing of 3D printers
- Local manufacturing remains dependent on centralised, industrialised processes hindering benefits in terms of appropriateness and bio-interaction
- Capacity for local manufacturing needs to be developed

Use and maintenance

- Great learning benefits for locally assembled or manufactured 3D printers
- Adaptability, accessibility, and appropriateness are enhanced through locally assembled or manufactured open-source 3D printers
- Fully open-source 3D printers are significantly more affordable, adaptable and accessible in terms of maintenance, education and experimentation
- Participation in 3D printers lifecycle cultivates more sustainable 3D printing practices

Fig. 2. Summary of MCT findings for the 3D printers life cycle.
Certain figure elements were sourced from www.pngegg.com.

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 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

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[1] https://materiom.org/.

[2] https://preciousplastic.com/.

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.

Authorship contributions

Category 1

Conception and design of study: C. Priavolou, K. Troullaki, C. Giotitsas, V. Kostakis;

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Drafting the manuscript: C. Priavolou, K. Troullaki, N. Tsiouris, C. Giotitsas, V. Kostakis;

Revising the manuscript critically for important intellectual content: C. Priavolou, K. Troullaki, N. Tsiouris, C. Giotitsas.

Category 3

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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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 et al. (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 et al. (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 et al. (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

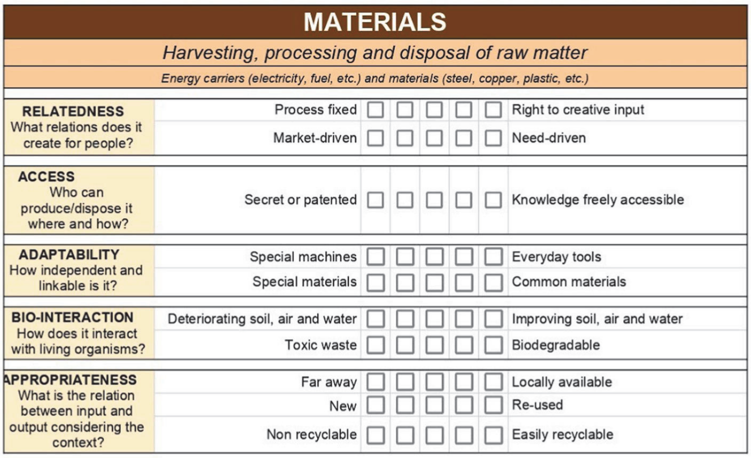
Focus area	Questions
Model specifications	- How many different 3D printers have you used or produced? - Can you give us details about the supported materials, the print volume and the layer resolution of the 3D printer(s)?
Open-source	- Have you ever used or produced an open-source 3D printer? - Compared 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 touchscreen	Color LCD touchscreen	IPS touchscreen	LCD screen	No	Yes	Yes	Color LCD touchscreen	Yes	Optional
Price	€2500 - 3000	$999 (Production stopped)	$1500	~€2000	~€770-1000	$2000	~€1000	~€2500	€2475	~€2500	€487-658

Appendix D



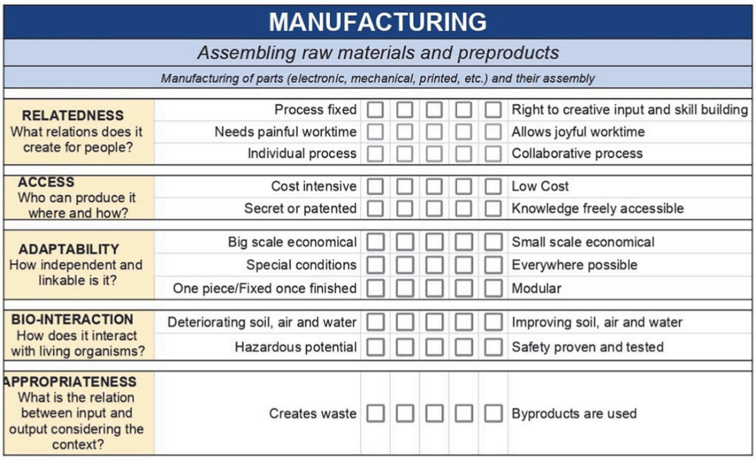
MATERIALS

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

Fig. D1. Adapted version of the MCT - Materials



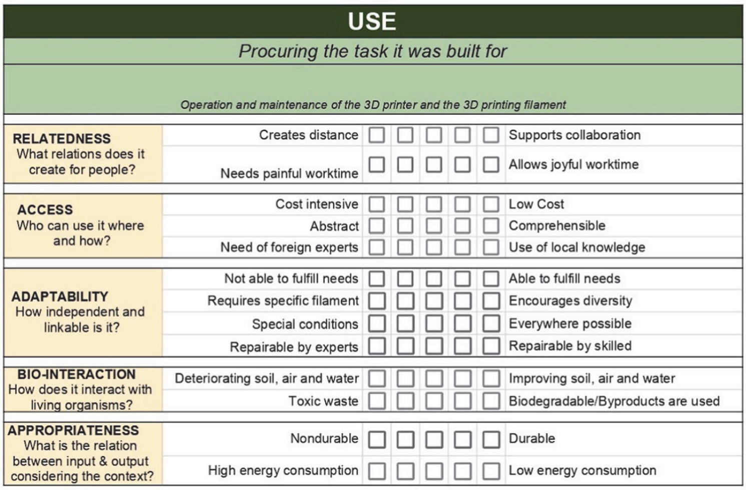
MANUFACTURING

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

Fig. 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

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How to unite local initiatives for a more sustainable global future

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ABSTRACT

This article challenges the belief in high-tech solutions to solve socio-environmental crises, proposing a political vision beyond "green growth" and "ecomodernism.". It advocates for a commons-based technology framework, promoting collective resource management for sustainability. We thus introduce "cosmolocal" production, a configuration that strives to connect communities around shared resources and serve their needs while minimizing ecological impact. Despite acknowledged tensions, we contend that the cosmolocal framework could foster institutional and social change, aiming to address environmental degradation and wealth inequality. To support this contention on cosmolocal production's potential, we point to several successful examples from the open-source technology paradigm.

Introduction

The world is crumbling around us, as global wealth inequality deepens and environmental degradation escalates alarmingly. Humanity is grappling with an unprecedented existential crisis. It is imperative that –the most forward-thinking segments of– our societies take action promptly. However, during the period of neoliberal capitalism's indisputable dominance, the daunting question of how people can affect change remains dangling. Capitalist values have become deeply entrenched in our societies and institutions. They are dictating and shaping our conduct in various aspects of life, from how we design and produce to how we interact, raise our future generations and form relationships.

Contrary to the calls to resign ourselves to the belief that there is no viable alternative to neoliberal capitalism, our situation is not devoid of hope. We explore new opportunities and challenges to address two pressing and closely intertwined issues of the Sustainable Futures scholarship and praxis: environmental degradation and global wealth inequality. This article argues that dispersed initiatives of "cosmolocal" production have indicated hints towards a more socio-environmentally sustainable future.

Why can high-tech be problematic?

In a state of emergency, it is audacious to place all our hopes for tackling the ecological crisis and wealth inequality in technology –worse even, in technology that is yet to materialize. This latter notion is incremental in the currently prevailing narratives such as "green growth" [1], "ecomodernism" [2], or "accelerationism" [3] which pin our aspirations on high-tech solutions. One can find advocates of these narratives all across the political spectrum. However, they are all united in the conviction that advanced technologies, like off-shore wind turbines, solar panels, smart sensors, 3D printing, artificial intelligence, and future highly efficient innovations, will pave the way out of the dead end. They suggest that we will manage to harness the benefits of high-tech to enhance service effectiveness and efficiency, reduce resource consumption and carbon emissions, boost productivity, and foster greater civic engagement. Although we have not only failed in doing so thus far but have caused a social, economic and environmental catastrophe along the way.

Hence, it is crucial to comprehend and address the issues inherent in the processes underpinning the production of high-tech artifacts. These issues are intensive resource extraction, labor exploitation, heightened energy consumption, and the excessive material demands often associated with high-tech products. The latter requires rare metals and scarce minerals, often sourced under dubious labor and environmental conditions in the Global South while benefiting primarily the Global North [4, 5]. The production, use, recycling and disposal of high-tech artifacts consume large amounts of energy, generate toxicity, and often involve dehumanizing and precarious working conditions [6]. High-tech is not unsustainable in its essence, but its scale and mode of production in the capitalist realm are.

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The root causes of environmental degradation and global wealth inequality, as well as potential solutions, do not reside solely in the realm of technology. Instead, the crux of the matter is profoundly political. The development and production of technology in the modern era are intricately interwoven with wealth inequality and environmental deterioration. Technology is not being produced in a vacuum, thus it is not neutral [7]. On the contrary, it is highly influenced by the decisions of manufacturers, legislators, consultants, designers and everyone else involved –directly or indirectly– in the process. In a globalized world, these decisions have global effects. Failure to consider the resources utilized and impacts produced internationally could result in identifying positive steps towards sustainability locally for some nations –primarily from the Global North– that relocate impactful activities overseas –primarily to the Global South. Conversely, the most affected countries in the Global South might undervalue the amount of negative externalities they are absorbing to accommodate impactful activities aimed at fulfilling other countries' consumption demands [8,9].

Technological artifacts reach consumers as polished products exchangeable for money, concealing the harsh realities of their design, manufacturing, global logistics, and eventual disposal [10]. Consequently, the comfort derived from technology often comes at the expense of distant humans and ecosystems, resulting in abundance for a privileged few and scarcity for the many. The extent to which one tolerates this predicament is fundamentally a matter of political discourse.

Furthermore, those advocating for a technical solution to address ecological breakdown and wealth inequality often champion more efficient production methods. However, they may inadvertently disregard some of the consequences that come with efficiency improvements, i.e., rebound effects. The Jevons Paradox, a critical insight attributed to the 19th-century British economist Stanley Jevons, reveals how efficiency gains can lead to a net increase in consumption due to reduced unit prices and a subsequent surge in demand [11]. For instance, the advent of more efficient steam engines enabled cheaper transportation, catalyzing the industrial revolution. Paradoxically, this did not result in a decrease in fossil fuel usage but instead drove it up [11]. When more efficient machines consume less energy, they become more affordable, prompting increased usage. This amplifies considerably when considering individuals like the super-rich global 1 %, who can utilize such technology on a significantly larger scale, with carbon footprints thousands of times greater than the average citizen [12,13]. Consequently, overall energy consumption experiences a substantial uptick.

Similarly to the case of the steam engine, in the late 90′s the introduction of computers, the Internet and e-mail in organizational procedures led many to believe that paper consumption would decrease drastically. However, a 2003 book titled *The Myth of the Paperless Office* showed that paper consumption increased, e.g., consumption of the most prevalent type of office paper (uncoated free-sheet) increased by 14.7 % in the U.S. between the years 1995 and 2000 [14]. Even with improved displacement technologies such as smartphones, mobile Internet and e-readers, paper consumption still has a slightly upward trend [15].

In contemporary capitalist societies, people tend to consume more when they have the means to do so [16,17]. Yet, what incentivizes the constant strive for efficiency at all costs? Could it be the growth imperative, i.e., the politically mandated push for continuous increase in the Gross Domestic Product (GDP) metric, influencing such behavior? Who designed this metric, who made the decision, and for what reasons, to prioritize this metric over others? Would "more efficiency" be justified if one accounted for the genuine costs associated with the labor of African or South American workers and the environmental destruction required for their production in the first place? Shouldn't governments consider the comprehensive social and environmental costs associated with the production of more efficient technological artifacts? Any plausible response to these multifaceted complex inquiries would have to delve into the processes through which people govern themselves, engage in deliberation, decision-making, and the challenging or perpetuation of existing institutions. Furthermore, conflicts, divergent choices, and unequal power dynamics dictate the outcomes of these processes [16,17]. In essence, any conceivable answer is inherently political.

The emergence of an alternative technology framework

This article discusses an alternative technology development framework, with the commons at its core. The commons represent social systems through which communities collectively manage shared resources [18,19]. Tangible examples of alternative institutions for a more sustainable societal organization have emerged and continue to emerge within the commons sphere. Just as Adam Smith used his renowned pin factory to illustrate the possibility of a different mode of production in the late 18th century (later recognized as "capitalist production"), a diverse range of commons-based "pin factories" foreshadow alternative approaches to addressing the key challenges of the 21st century.

The term "technology" doesn't solely pertain to the artifact as an object; it encapsulates everything related to its existence, from design and manufacturing to usage, maintenance, and disposal, including the knowledge associated with it [20,21]. The objective, therefore, is to explore methods for instilling technology with socially and ecologically sustainable values. We contend that a cosmolocal production configuration could potentially usher in a more democratic and ecological global political economy. A configuration that captures the essence of dispersed initiatives and technology movements, which appear to prioritize socio-environmental well-being over profit maximization, excessive production and consumption.

The concept of cosmolocal production has arisen in tandem with the proliferation of digital communication networks [22]. It entails the approaches used to connect local communities within networks of shared resources with the aim of reducing material and energy footprints, without outsourcing the adverse impact on other ecosystems [23,24]. Cosmolocal production redefines the communal aspect [25] in terms of location, establishing resilient infrastructures for the exchange of knowledge, techniques, and practices over open communication channels [26]. Design, knowledge, and software are collectively developed and enhanced as part of a global digital commons, while manufacturing occurs locally, with due consideration for local

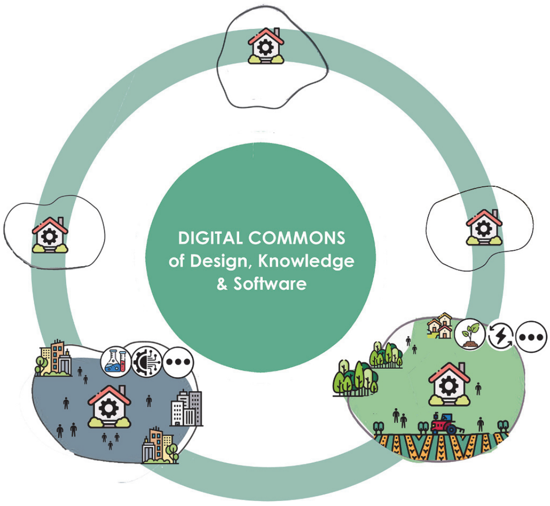

Fig. 1. The cosmolocalism structural framework with its functions (e.g. knowledge transfer), spatial dimensions (e.g. local/global, rural/urban), and main fields of activity (e.g., agriculture, digital technologies) [24].

biophysical conditions (see Fig. 1 for an overview of the cosmolocalism structural framework) [26,27].

Cosmolocal production neither demonizes high-tech nor idealizes low-tech. Rather, it employs the concept of "mid-tech" which encompasses the notion of achieving equilibrium between two diametrically opposed qualities: high-tech and low-tech. Mid-tech functions as a comprehensive intermediary that transcends the high-, low-tech polarity and molds them into a more integrated synthesis, reaping the benefits of the two extremes. Consequently, high-tech and low-tech cease to be mutually exclusive; instead, they form a dialectical unity. A mid-tech approach delves into the capacity to harmonize the efficiency and seamlessness of high-tech with the autonomy and resilience inherent in low-tech [28]. Kostakis et al. [28] exemplify the mid-tech notion by juxtaposing high-tech prosthetics with the case of OpenBionics, an open-source initiative that combines high-tech and low-tech elements to build lightweight, affordable and adaptable prosthetic devices. High-tech prosthetics utilize complex sensors and actuators and require sophisticated human-machine interactions for efficient operation. As a result, they are expensive, heavy and difficult to use, maintain and/or repair. In contrast, OpenBionics strives to develop prosthetic devices that are easily reproducible using readily available materials and rapid prototyping methods [28]. OpenBionics embraces the cosmolocal practices of global digital commons and on-demand, needs-based local manufacturing.

Many more technology initiatives serve as prime examples of cosmolocal production. Take, for instance, Wikipedia, a free and open-source encyclopedia that has supplanted the Encyclopedia Britannica and Microsoft Encarta. Wikipedia is created and maintained by a community of widely dispersed enthusiasts primarily motivated by reasons beyond profit maximization. Likewise, in the realm of software, consider GNU/Linux, which powers the top 500 supercomputers, or the Apache Web Server, the dominant software in the web-server market. These accomplishments are the result of collaborative efforts by communities of hackers, scientists, and enthusiasts where the profit incentive is present but relegated to the periphery. Arguably, humans are activated by a rich motivational diversity, which may include the incentive to satisfy a particular need or the pleasure of creativity, sharing and learning [27].

Similarly, the rise of networked micro-factories is giving birth to niche initiatives in design and manufacturing. These spaces, which can be makerspaces, fab labs, or other co-working facilities, are equipped with manufacturing technologies, including 3D printers, CNC machines, as well as traditional low-tech tools and crafts. These initiatives form a diverse tapestry that doesn't require a singular physical base since their members are scattered across the globe. Prominent examples are the L'Atelier Paysan cooperative and the Farm Hack network, which develop open-source agricultural machinery for small-scale farming [21]; the Libre Space Foundation, responsible for the first open-source satellite in orbit; the OpenBionics project, developing open-source designs for robotic and bionic devices [24]; the Wind Empowerment Association, producing small-scale renewables [29]; or the RepRap community, crafting open-source designs for 3D printers capable of self-replication.

These initiatives harness a global wealth of knowledge to manufacture artifacts locally, enhancing them with their own contributions in the form of design files, software, best practices, and expertise. In cosmolocal production, local communities can diminish their reliance on global value chains because a substantial portion of the production cycle occurs at the local level [24]. Cosmolocal production often hinges on values such as reciprocity and self-organization, which prioritize local autonomy, cultural diversity, and a sense of common benefit [24]. These technology initiatives cultivate ecosystems of small-scale, locally-focused communities that nurture the communal capabilities of individuals and groups, contributing to the global digital commons [23]. The globally spreading digital commons in combination with localized manufacturing capabilities generate hybrid forms of commoning that scale wide or out instead of scaling up [24].

Cosmolocalism embodies both capitalist and post-capitalist aspects, drawing viability from partnerships with the dominant system while pointing toward new possibilities. The elements that separate cosmolocal production from the conventional industrial production are design-embedded sustainability, i.e., products are designed for longevity; needs-based manufacturing, i.e., sourcing materials locally to minimize logistics; and access to the means of production, i.e. digital and physical infrastructures are shared [24]. However, cosmolocal production is not without its tensions and contradictions. For instance, although it may alleviate the pressure on natural resources and local populations (e.g., minerals from African countries), it still relies on energy- and material-intensive infrastructures, such as the Internet. Nevertheless, this article argues that a cosmolocal framework could act as a catalyst to connect the multitude of local initiatives and unite their radical narratives while preserving their diversity.

Conclusion

The most urgent challenges of our time are intricately connected with technology. The evolution of technology within the capitalist mode of production presents numerous pressing issues, leaving a profound impact on societies and the environment. The relentless pursuit of constant upscaling and economic growth inherent in capitalism places an immense strain on human and material resources, pushing our world close to a catastrophic tipping point. As a response to this impending crisis, various post-capitalist narratives have emerged, signaling an inevitable transition in the mode of production.

In this context, we argue that nodes of cosmolocal production may serve as beacons toward a more inclusive and sustainable future. While some may perceive these examples as modest or even utopian, their uniqueness lies in the reclaiming of lost elements through empowerment and capacity-building, blending traditional and modern methods. It is crucial to view these cosmolocal endeavors as more than just idyllic visions. They represent pilot projects, offering a glimpse into a transformative shift in our production approach. They demonstrate the possibility of an alternative localization and a different form of globalization.

However, caution must be exercised to prevent the absorption of these initiatives by the prevailing dominant context, recognizing potential risks and challenges such as the dependence on energy- and labor-intensive infrastructures like the Internet. Despite this, the counterculture is not merely present but steadily gaining ground. While to reap the benefits of cosmolocal production strong political initiative and institutional innovations are needed, the momentum behind these post-capitalist pathways signifies a growing potential for meaningful change in our approach to production.

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CRediT authorship contribution statement

Vasilis Kostakis: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft. **Nikiforos Tsiouris:** Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability

No data was used for the research described in the article.

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ORIGINAL ARTICLES

An Alternative Approach to Science and Technology Parks

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Abstract

Science and technology parks (STPs) are fundamental elements of the knowledge economy infrastructure. They are clusters of research and development, innovation and technology transfer. However, they often tend to endorse specific trajectories for technological and business development, such as the production of high technology and the proliferation of profit-maximising businesses. In response to an intense environmental and socio-economic crisis, this article explores how STPs could facilitate a postdigital science and technology development, reaping the benefits of open-source technology and social entrepreneurship. The article aims to outline an alternative approach to designing and operating STPs through an exploratory case study from Greece. By embracing a postdigital and commons-oriented approach, STPs could promote technology and business diversity, which might help address environmental degradation and wealth inequality.

Keywords Science and technology parks · Commons · Postdigital · Open-source technologies · Social and solidarity economy

Introduction

Science and technology parks (STPs) are often considered to be fundamental, even traditional (Frischmann 2012) infrastructure elements bolstering the knowledge economy. They aspire to realise local collaborations and enhance regional innovative and economic performances (Albahari et al. 2017; Laspia et al. 2021). To fulfil these aspirations, STPs tend to promote the production of high technology and profit-maximisation business models. However, it is important to reconsider environmental and socio-economic consequences caused by high-tech development, the so-called digital revolution, and profit-maximisation business activities (Kallis et al. 2018; Kostakis and Tsiouris 2024).

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In response to the high-tech and profit-maximising fixation of the conventional STP paradigm, I draw inspiration from postdigital theory and the commons. Postdigital theory posits that the digital is no longer novel, as high-tech disruptions have become commonplace, and recognises the need to look further than analogue–digital dichotomy (Jandrić et al. 2018; Macgilchrist 2021; Jandrić 2023a). Digital technology has taken a specific form in people's minds and the postdigital brings the opportunity to break the norms and provoke change. The essence of postdigital ideas does not lie in a linguistic shift but a cultural one (Sinclair and Hayes 2019). An STP that persists in a digital revolution will more likely continue to have similar results. A postdigital STP approach challenges the norms and could create new pathways, friendlier to both humans and the environment. At the same time, the commons showcase a more inclusive and sustainable way of organising our societies, an alternative proposition that harnesses a global wealth of knowledge to localise and democratise production (Kostakis and Tsiouris 2024).

High-tech development is burdened by plenty of problematic processes. The use, production, disposal, and even recycling of high-tech artefacts is often an energy-consuming, toxic-generating, and labour-intensive process marked by inhumane and precarious conditions (Lange et al. 2020; Sovacool et al. 2020). Further, high-tech advancements are often proven environmentally and economically unsustainable by products' short lifespan and planned obsolescence in an attempt to achieve exponential economic growth (Kostakis et al. 2018). Although in many cases high-tech increases efficiency, it can also result in rebound effects that end up neutralising its positive impact in terms of socio-environmental sustainability (Kallis et al. 2018). Similarly, for-profit-maximisation business activities regularly ignore environmental boundaries and exploit socio-economic inequalities, creating wealth and comfort for the few at the cost of the many (Kallis et al. 2018; Kostakis and Tsiouris 2024).

In contrast, there is a multitude of potentially more collaborative and inclusive business- and technology-development models that are inspired by, and correlated with, the commons. Examples include the open cooperativism movement (Pazaitis et al. 2017), the platform cooperativism movement (Scholz and Schneider 2016), and the open-source movement (Kostakis et al. 2018). The commons are social systems where a shared resource is collectively managed by the community or group of stakeholders that produces, maintains, and protects that resource (Bauwens and Jandrić 2021). Movements and initiatives organised around the commons aim not to maximise profits but to maximise public value through sharing the acquired knowledge openly (Pazaitis and Drechsler 2020). The profit motive is not absent, but it is relegated to the periphery (Benkler 2011). Humans are activated by a rich motivational diversity, which may include the incentive to satisfy a particular need or the pleasure of creativity, sharing and learning (Benkler 2006; Weber 2004).

This article provides a constructive critique of the established views and practices around STPs. It offers an alternative approach for establishing more pluralistic STPs, which could serve as hubs towards a more sustainable technology and economy. To realise these goals, I use an exploratory case study from the Region of Epirus in Greece that tentatively frames two commons-oriented emerging phenomena, open-source technologies and the social and solidarity economy, within the planned-to-be built local STP.

The article proceeds with a review of the characteristics and challenges of conventional STPs regarding technology, business, and governance. Then, I underline potentialities of an alternative technological and business approach and an exploratory case study where a citizens' initiative advocating for an alternative STP is introduced. Next, I discuss the case study in conjunction with postdigital theory and the commons. The article lists some benefits that STPs could reap by pursuing a more pluralistic approach amidst a profound environmental and socio-economic crisis.

Conventional STP Approach

Literature around STPs is extensive yet characterised by a sense of ambiguity (Lecluyse et al. 2019). The latter becomes apparent already by the lack of a concise, universal definition of an STP. According to one definition, STPs function as regional clusters of organisations such as universities, research institutions, and other private and public entities, where human, material (machines, tools, and infrastructure) and immaterial (knowledge) resources are accumulated in one physical location with the purpose of creating positive social and economic impact through innovation and technology transfer (Xie et al. 2018).

STPs share a core of similar elements, which are the spatial specificity, the R&D and innovation orientation, the knowledge and technology transfer between stakeholders, and the proximity—in terms of distance and involvement—to a university or other higher education institutes (Hobbs et al. 2017). Commonly, STPs bring together and host organisations that specialise in a specific field of science and technology, i.e., the biotechnology parks in India (Vaidyanathan 2008) or the Wuhan Donghu High-Tech Zone on information technology and electronics (Xie et al. 2018). The proximity to entities with a similar specialisation seems beneficial for companies on several levels, from enabling collaborations to the more direct exchange of knowledge and access to state-of-the-art developments in the field (Xie et al. 2018).

STPs in 'advanced' economies are almost always formed by an alliance between scientists and private investors, whilst in emerging economies, STPs are mostly a government-planned project to spark high-tech innovation within an area as part of a regional development plan (Lau and Lo 2015). In both cases, public-funding is ubiquitous as the government sets up financial institutions to compensate for the lack of investment support start-ups or other tenant companies could be facing (Vásquez-Urriago et al. 2016). The level of private sector involvement and its impact on the performance of STPs remains a subject of debate. Although some authors argue more private sector involvement benefits STPs (Chen et al. 2006; Sofouli and Vonortas 2007), there is no conclusive evidence that this is indeed the case (Albahari et al. 2022; Lecluyse et al. 2019).

Collaboration of universities and STPs has often presented positive spillovers on the development of the regional and local economy, by raising the level of performance in the universities and increasing employment opportunities in the region (Link 2016; Mora-Valentín et al. 2018). Technology development and transfer may instigate a relationship between universities and companies that proves to be mutually beneficial. Universities can attain R&D funding and secure their intellectual property interests and rights, whilst gaining a reputation for their innovation potential and using licensing revenues to finance further research in the institution. Conversely, companies can potentially significantly reduce R&D costs and capitalise on the produced technologies (Steruska et al. 2019).

Companies' participation in an STP is incentivised by favourable rent prices and locations, and technical services that are easily accessible on-site (Ng et al. 2022; Steruska et al. 2019). The spatial proximity enables a dense networking activity facilitating the creation of informal, diverse relationships between stakeholders, which in many instances leads to successful synergies (Poonjan and Tanner 2020). Location, local context, and pre-existing competencies in terms of governance structure and innovation culture in the region usually have a significant effect on the development of an STP. That is because, on the one hand, universities and research institutions tend to dictate, to a large extent, the kind of technology companies are able to commercialise and, on the other hand, national or local governments are in charge of innovation promoting policies (Ng et al. 2022; Poonjan and Tanner 2020; Vásquez-Urriago et al. 2016).

High-tech is perceived as a prerequisite for STPs, whilst other technological approaches seem to remain unexplored. Most funding for STP development arrives from public sources but the impact on local stakeholders and society has been far from what was initially anticipated; some authors even consider STPs as high-tech fantasies (Bakouros et al. 2002; Massey and Wield 2003). Regional socio-economic problems involve many more parameters than the mere implantation of a high-tech cluster can solve. At the same time, the high-tech approach coupled with private-sector involvement has shown to increase the development gap between regions (Massey and Wield 2003; Vedovello 1997). Conventional STPs have achieved mixed results in fulfilling their purpose of positively transforming the social and economic status of a region (Albahari et al. 2022; Hobbs et al. 2017). I argue that there are alternative technological and business approaches that have indicated nodes of success in spurring innovation and enhancing sustainability and could translate favourably within an STP context.

A Postdigital and Commons-Oriented Approach

STPs have been prevalent around the globe for more than half a century with their total number being in the hundreds (Sandoval Hamón et al. 2022). However, so far they have shown mixed results in fulfilling their presumed goals to the initially expected level (Albahari et al. 2022; Lecluyse et al. 2019). This opens room for experimentation, in this article, with a postdigital and commons-oriented approach. The postdigital, much like the commons, represents both a disruption and an extension of the digital revolution and brings forward a grand challenge across science, education, arts, and other areas of human interest (Jandrić et al. 2018; Macgilchrist 2021). In this case, the disruption represents a tipping point where the old notion, i.e., the digital, is arguably no longer sufficient and a new notion emerges moving forward, i.e., the postdigital. Similarly, it may be time for STPs to steer away from their conventional digital approach and explore a postdigital one.

Fixating on high-tech production, STPs often remain stagnated. Beyond grave environmental consequences and inhumane working conditions (e.g., mining in Africa and precarious labour in Asia), artificial monopolies and planned obsolescence (e.g., Monsanto's seed monopoly or Apple's support policy on its devices and services), high-tech is usually locked behind patents and proprietary licences (Boldrin and Levine 2013; Pazaitis et al. 2021). In contrast, a commons-oriented open-source approach allows users to study the technology, use it, reproduce it, develop it, and adapt it to their needs (Weber 2004). Closed technology restricts those freedoms and minimises the agency of the users.

An exemplary case of the benefits of open over closed technologies is 3D printing. Since the FDM patent expired, knowledge has been open to everyone, and thousands of people have experimented with it innovatively, accelerating the rate of development around it (Priavolou et al. 2022). A similar situation occurred 220 years ago, with the steam engine that catalysed the Industrial Revolution (Nuvolari et al. 2011). When closed technology became open, innovation around technology increased exponentially. The patent system is outdated and does not seem to spur innovation but rather interrupt it (Pazaitis et al. 2021). Conversely, the aforementioned examples showcase how innovation can be amplified by being managed as a shared resource, i.e. a commons.

High-tech is not by definition socially and environmentally unsustainable. However, when produced 'within silos' being profit-incentivised, it has a detrimental effect on societies and the environment (Kostakis and Roos 2018; Lange et al. 2020). Open-source technological products can also be high-tech but are mostly produced in a way that may mitigate some of high-tech's challenges. Humans regain some control over technology; a significant part of production can be localised; and an optimal synthesis can be achieved between the efficiency and seamlessness of high-tech and the frugality and resilience of low-tech (Kostakis et al. 2023a).

The latter intersects with a postdigital perspective in which the digital element makes part of a comprehensive totality, prompting a more critical stance to understanding technology and its practical applications (Fawns 2019). Technology is an object but also includes processes and knowledge produced around the object. Opposing the deterministic digital perspective, technology is not neutral but socially defined. It is highly influenced by the decisions of manufacturers, designers and anyone else—directly or indirectly—involved (Kostakis and Tsiouris 2024). Postdigital theory illuminates the complex relationship between humans and technology. It highlights the imperative for humanity to ponder the profound ramifications of its continuously more intricate interaction with digital technologies—an urge to comprehend and scrutinise the human-technology connections (Jandrić et al. 2018; Green 2021; Jandrić 2023a).

The open-source paradigm has already been integrated into global organisations. A report commissioned by the Ford Foundation (Eghbal 2016) concludes that almost all software 'used by Fortune 500 companies and governments is based on FOSS: from Apache, the most popular web server, to GNU/Linux, on which the top-500 supercomputers run, to WordPress, the most popular content management system, to OpenSSL, the most popular encryption protocol to secure transactions' (Pazaitis and Kostakis 2022). In the realm of hardware, there is a bloom of initiatives worldwide that produce OSH (Blind et al. 2021). For example, in a small country like Greece, one can find open-source initiatives that produce various technologies such as agricultural machinery,[1] robotic and bionic devices,[2] small-scale wind turbines,[3] and satellites.[4] We have come to the point that open-source technology is gradually recognised as a possible alternative not only by the likes of The Economist and Forbes but also by huge consulting companies such as Deloitte and PricewaterhouseCoopers (Pazaitis and Kostakis 2022). This should serve as a warning that the commons could and have been co-opted as capital and remind communities to take care of and protect their commons (Bauwens and Jandrić 2021).

Open-source technologies go beyond the technical and generate positive spillovers in the business and governance sphere. The latter effect derives from the non-negligible tendencies of the commons-oriented approach, which is pervaded by the elements of transparency, inclusion and sustainability (Priavolou et al. 2022). Open-source boosts innovation, empowers communities through collaboration, and amplifies local economic and social impact (Robra et al. 2023). Therefore, open-source technologies are incremental for the social and solidarity economy (Gagliardi et al. 2020). The economy is dominated by profit-driven corporations that exploit human labour by doing business as usual, whether that is in subcontracted sweatshop factories and warehouses, in typical companies, or in 'agile' teams and user groups (Pazaitis and Kostakis 2022).

In contrast, commons-inspired initiatives such as social enterprises and open cooperatives are often more resilient than those aimed at maximising profits; benefit the local communities; and tend to operate in a more democratic way (Esteves et al. 2021). Some even foresee that a social and solidarity economy could become the vehicle to achieve the Sustainable Development Goals set by the UN (Esteves et al. 2021; Gagliardi et al. 2020). Social enterprises, and more so open cooperatives, adopt multi-stakeholder democratic governance models, enable their community to mutualise resources and organise around social and environmental global issues (Pazaitis et al. 2017). STPs are incubators of innovation and technology development. Therefore, aspiring STP designers, directors, and other stakeholders should explore those possibilities.

The Case of the OpenTechPark-Citizens for Open-Tech

This article employs an exploratory case study to tentatively frame an alternative approach to STPs (Yin 2009). The latter builds on the conjunction of two emerging collaborative movements: open-source technologies, and the social

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[1] See https://www.tzoumakers.gr/english/. Accessed 20 June 2024.

[2] See https://openbionics.org/. Accessed 20 June 2024.

[3] See https://neaguinea.org/. Accessed 20 June 2024.

[4] See https://libre.space/. Accessed 20 June 2024.

and solidarity economy. The case study involves a grassroots initiative from the Region of Epirus in Greece. The initiative, called OpenTechPark-Citizens for Open-Tech (COT), is critical of conventional STPs and goes on to provide a set of proposals for an alternative STP. The critique and the proposals are informed by a year-and-a-half-long public deliberation, in which various stakeholders and experts have participated. The set of proposals has been co-configured through a series of iterative cycles of participant feedback.

I adopt a participatory approach to case study research, where case participants become contributing researchers and, hence, experts who can contribute to understanding the underlying processes (Reilly 2010). This article is developed subjectively mainly through personal observations and interpretations and proceeds to suggest a normative STP framework. I aim to further theorise it within the postdigital theory and the commons through my subjective interactions and experiences as a member of the COT initiative.

The case study takes place in Epirus, where the regional government decided to contribute tens of millions of euros and acres of public land to create a high-tech park in the regional capital, Ioannina. Specifically, the submitted budget was 49 million euros, from which 20 million would be covered by the Recovery and Resilience Facility. The remaining 29 million would be covered half by loan and half by rent advancements from companies. The decision to create a high-tech park was taken without any public deliberation on whether the city needs a technology park, and if so, what kind of technology park should that be.

In early 2021, the P2P Lab, a local social enterprise that studies technology and its impact on society and the environment, noticed the regional government's plans. Reflecting on my own positionality (Hayes 2023), I am a core member of the P2P Lab as well as a participant in the later-formed COT initiative. Initially, as a collective of researchers and activists, we published an open letter advocating for an open-tech park seeing that an STP built with public funding and on public land should enable sharing, collaboration, and local socio-economic impact. Soon after, an online consultation for an alternative technology park was held. The consultation, in which 217 scientists and citizens participated, began on the mailing list of the P2P Lab and produced a set of policy proposals for a different STP. It should be clarified that all participants in the consultation were familiar with, and their work relates in some capacity with, the two main concepts that permeate the proposals, i.e., open-source technologies and the social and solidarity economy. To a degree, this influenced the tendency of the proposals towards these concepts.

Subsequently, the under-formulation grassroots initiative issued an invitation (via relevant mailing lists, the P2P Lab's social media, and a press release that was published by most local media) to an open online—due to COVID-19 restrictions—meeting to discuss the first iteration of proposals. The Governor of Epirus formally denied this invitation and dismissed the goals of the initiative through an exchange of registered letters via regular mail. During the online meeting that led to a second iteration of the proposals, it was unanimously agreed that two of the members—myself being one—would be tasked to represent the initiative and convey its proposals in person to more local stakeholders. Moreover, a website (opentechpark.org) would be created to document the initiative's progress. The website is bilingual and is regularly updated with relevant developments.

In the following two months, the initiative's members met and discussed with individuals and local organisations, such as the Head of the Chamber of Commerce, the Mayor of Ioannina City, social enterprises, social movement groups, and other Epirus-based networks. Moreover, argumentation of the COT initiative was communicated to the leaders of two opposition parties of the Greek parliament and the Minister of Digital Governance. A think tank, affiliated with one of the two opposition parties, organised a public event in Athens in which the goals of the COT initiative were discussed in person with almost 100 participants (members of the parliament included). Another open online event followed on the topic, which was co-organised with the Athens-based Open Technologies Alliance[5] (GFOSS). The above-described activities aimed at the expansion of the initiative's network and the collection of further feedback.

A continuous public deliberation took place indirectly and asynchronously through a mailing list that was created for the coordination of the COT initiative. After having publicly documented the process stage by stage, the initiative reformulated eight proposals which were then submitted via mail to the Region of Epirus. The letter was followed by a request to discuss the proposals in the Regional Council of the Region of Epirus, as well as in the Municipal Council of the Municipality of Ioannina. The proposals were also shared with the deputies of the Region of Epirus.

The COT initiative suggests that public infrastructures should facilitate the sharing of knowledge. The list of proposals[6] regarding the high-tech park that was submitted to the Region of Epirus by the COT initiative is, as follows:

1. To establish a public co-working space. This way, freelancers and students will use this space, facilitating collaborations and knowledge exchange. The park could also attract people who work remotely in technology and look for places to settle temporarily (digital nomads).
2. To establish a makerspace. All citizens will be able to access it, but priority will be given to businesses housed in the park, to schools and the local university. Connecting the communal makerspace to the local economy (e.g., agricultural production, livestock, and wineries) may provide solutions for primary production in terms of automation, control and digital switching solutions. Knowledge is produced locally and creates value for the region.
3. To integrate direct democratic processes for the administration of the co-working space and the makerspace by the citizens and the entities that are active there.
4. To provide benefits (e.g., rental discount) to park-based businesses that produce open technology (e.g., FOSS and/or OSH) and/or have integrated circular economy elements in their organisation. If the company can demonstrate the impact

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[5] See https://gfoss.eu/. Accessed 20 June 2024.

[6] Details of specific local context, such as names of local organisations, were omitted to facilitate the reader and prevent confusion.

of its open product or service in the Region of Epirus, benefits would be even greater.

5. To provide benefits to social and solidarity economy entities that deal more widely with technology. Such companies have cooperative/participatory structures, and thus significant impact on the local economy.
6. To be open and easily accessible to the local community. In the design phase, needs of people with disabilities (e.g., ergonomic office design, area access, and toilets) as well as general diversity (race, gender) should be taken into serious account.
7. To encourage development and operation of clean energy communities to increase the energy autonomy of Epirus.
8. To promote interaction and cooperation between the public and private sectors. A good starting point may be to organise training seminars for farmers and producers/designers throughout Epirus.

The proposals were discussed during a Regional Council that took place online on 25 May 2022 with the participation of some of the initiative's members. In November 2022, the Recovery and Resilience Facility formally approved part of the funding needed for the construction of the park. The COT initiative's actions resulted in the Region of Epirus including most of its proposals in the master plan that was submitted to the respective ministries. Thus, one of the STP's buildings shall be dedicated to entities that produce open-source technologies and promote the social and solidarity economy. Although the inclusion of the initiative's proposals is a positive outcome, the next steps of design and implementation will be critical. At the time of this writing, the plan for the local STP has not come to fruition.

As a participant in the COT initiative, I recognise potential academic contributions from this exploratory case. The initiative has managed to contour a more inclusive and socio-environmentally sustainable STP based on the diffusion of open-source technologies and the promotion of the social and solidarity economy. I do not aim to provide a definite objective masterplan of how STPs should operate. Instead, I build on this case to suggest a normative, more pluralistic approach, which connects with postdigital theory and the commons.

Discussion

STPs have traditionally aspired to a high-tech path (Massey and Wield 2003) that provides advanced, sophisticated solutions but often also causes grave problems (Sovacool 2019). In most cases, it creates artificial abundance for the few and scarcity for the many—whilst even the privileged few have limited agency (Boldrin and Levine 2013). To an extent, these consequences could be addressed by the support and adoption of open-source technologies whilst aiming for an optimal middle ground between high-tech and low-tech (Kostakis et al. 2023a). One could consider it as a postdigital notion that transcends dichotomies such as online and offline, virtual and real, digital and analogue, and technical and natural (Macgilchrist 2021; Jandrić 2023a).

The COT initiative advocates for what Gorz (1968) would call a 'non-reformist reform'. Answering the question whether systemic change will emerge through reform or revolution, Gorz proposed that through non-reformist reforms, social movements could achieve immediate gains and actively prepare for a wider battle, eventually culminating in more radical transformations. The COT initiative is a social movement calling for a non-reformist reform in STPs. There is a wealth of knowledge, experience, and good practice produced within the postdigital and commons realm that could affect a sustainable, non-exploitative, non-reducible knowledge economy (Green 2021). As an integral infrastructure element of the knowledge economy, STPs should explore the benefits of this wealth. Having said that, a non-reformist reform of STPs will not come without the organisational and political challenges inherent to such institutions.

A commons-oriented open-source approach enhances co-creation and inclusion in the production of technology and accelerates innovation through sharing, showcased by the multiple successful projects ranging from agriculture to space technologies (Giotitsas 2019; Robra et al. 2023). In line with the values of openness and collaboration in the production of technology are the proposals of the COT initiative to include, in the local STP, co-working spaces; a community makerspace; and offer benefits to entities that produce open-source technologies. In accordance with the COT initiative's proposals, including an open community makerspace and a co-working area could be beneficial for an STP as they could function as a point of convergence for students, researchers, communities, and organisations. They could serve as places to meet, exchange knowledge and experience, and develop informal or formal relationships. Fostering an environment where people from different fields and backgrounds come together to create has shown to enhance innovation (Farritor 2017). Both relevant proposals are derivatives of the commons-oriented approach that the initiative, and me in this article, adopt. Makerspaces can serve as hubs of innovation, vehicles for needs-driven transformation (Niaros et al. 2017) and local economic development (van Holm 2017), all of which correlate strongly with the targets of an STP for increased local impact.

Although postdigital dynamics between technology, the makers, and the growth-oriented knowledge economy are complex, collective initiatives have managed to foster non-hierarchical patterns that encourage creativity, collaboration, and knowledge sharing towards successful innovations (Green 2021). Human relationships and praxis are vital for social innovation as it is aimed at avoiding ecological overshoots and socio-economic shortfalls whilst navigating paths towards a more just economy through the creation of collaborations, shared aspirations and infrastructure (Goodyear 2022). The strive for productive and purposeful human-technology relationships occurs simultaneously at a micro-level and a macro-level (Jandrić 2023b). Infrastructures such as STPs include both these levels and influencing them can contribute to radical change.

As STPs are set in a specific spatial context, they aspire to have a positive economic and social impact locally, e.g., attract companies and create professional opportunities for the locals, develop technological solutions for the region, and enhance the local innovation culture (Lau and Lo 2015; Ratinho and Henriques 2010). In more than half a century of existence, STPs have achieved some positive outcomes locally. There have been cases, however, that the development of STPs contributed to the mitigation of inequalities between, and within, regions by providing increased agency to private-interest initiatives and by staying confined in the high-tech pathway (Bakouros et al. 2002; Massey and Wield 2003; Vedovello 1997). The most prominent example is that of Silicon Valley which aspires to offer avant-garde efficient solutions, promising digital and other 'revolutions' sparked by big data and algorithms (see Jandrić 2024). There is an imminent problematisation over the actual social, and material influence of the digital, which contradicts the common fallacy that the digital is something without tangible consequences. Postdigital aims to 'hold the digital accountable' by looking beyond the promises of maximising efficiency and establishing a critical comprehension of implications of digital technologies on our society (Jandrić et al. 2018).

Whilst not dismissing the impact of conventional STPs, there are challenges that need to be addressed. For example, the COT initiative, keeping in perspective that the local STP will be primarily publicly funded, has proposed the enhancement of public–private sector collaboration through the STP's administration, the inclusion of diverse social groups in the different phases of the project, and the promotion of non-profit renewable energy communities in an effort to limit the issue of energy poverty in the region. Enabling communities to innovate and fulfil their needs in a spirit of collaboration, solidarity, and democratisation of technology has revealed glimpses into more sustainable and inclusive futures (Kostakis et al. 2023a, b). These arguments are deeply intertwined with a postdigital infrastructure where the social, digital, material, and all in-between aspects are embraced (Goodyear 2022).

STPs' focus on maximising profits and efficiency has been counterproductive (Chen et al. 2006; Laspia et al. 2021). STPs are multi-stakeholder entities with a strong public sector presence. There may lie an opportunity for STPs to adopt and promote the social and solidarity economy, which is characterised by more democratic governance models and a more social and political orientation (Gagliardi et al. 2020; Robra et al. 2023). Social cooperatives are intrinsically gravitating towards the common good and work on addressing global challenges, even if they operate on a local scale (Pazaitis and Drechsler 2020; Priavolou et al. 2022).

There are three main levels of resource allocation: the state, which represents regulatory planning, as in the capitalist system; the market, which regulates the allocation of capital; and the emergence of mutual coordination or 'stigmergy', which creates a friendly environment for open-source commoning. At the moment, we are experiencing an ecological, socio-economic crisis but also a crisis of democracy caused by the failure of the state and the market. That creates a pathway for a more sustainable response through the commons (Bauwens and Jandrić 2021). According to Bauwens and Jandrić (2021), the answer lies in the emergence of a public-commons cooperation pool that would legitimise products and services produced by communities and place them into existing systems. This idea goes hand in hand with Gorz's (1968) non-reformist reform. The COT initiative's approach to STPs could disrupt the existing system and legitimise postdigital theory and the commons by transferring them to an institutional level, managing publicly funded infrastructure as a commons.

Conclusion

This article tentatively synthesises good practices in technology, organisation, and business and provokes discussion around postdigital and commons-oriented infrastructure. It draws experience and knowledge from successful commons-inspired examples from the open-source movement and identifies multiple benefits for an alternative STP that adopts these approaches. The case of the COT initiative has been an opportunity to open the debate and construct some untapped potentialities regarding STPs. An exploratory case makes it hard to provide in-depth and robust findings. Nevertheless, it could be worthwhile for STPs to be more pluralistic and open, recognising the limits and inefficiency of the conventional approach and gathering the seeds from promising alternatives.

Postdigital theory disrupts dichotomies and reaches beyond the digital, shedding light on aspects that are explicitly or implicitly ignored. Respectively, the COT initiative disrupts conventional STP approaches. Not all disruptive movements correlate. In this case, however, postdigital theory and the initiative's alternative approach to STPs have a prevalent connection. They both explore and embed human relationships in technology, obviously with their imperfections but with an important and undervalued contribution. Following Sinclair and Hayes (2019), the *post*digital (com-*post*) is a fertile ground for sharing, collaborating, and producing science and technology that is socially and environmentally sustainable. Thus, the article opens a postdigital dialogue (Jandrić et al. 2019) between postdigital and STPs.

This article positions postdigital theory within the context of an STP. Postdigital theory has extensively discussed creative labour, digital learning, even universities. STPs bring together all these previously explored aspects, along with many others, which makes them an interesting experimental testbed for postdigital theory. The presented study is based upon an exploratory case study within the Western (Greek) context and should be expanded to and tested in other contexts. Therefore, the article's most important implication is opening a dialogue on exploring postdigital approaches in such an institution, enriching both postdigital theory and praxis of a multi-stakeholder complex institution like an STP. Based on a lot of recent good work related to studies of postdigital futures (e.g., Forsler et al. 2024), future research may inquire what a postdigital and commons-oriented STP would look like: should it be spatially centralised or distributed, should it concentrate on a specific field of science or opt for a more extensive variety, and so on.

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Declarations

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