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The convergence of digital commons with local manufacturing from a degrowth perspective: Two illustrative cases

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ABSTRACT

The emerging discussion about the sustainability potential of distributed production is the starting point for this paper. The focus is on the "design global, manufacture local" model. This model builds on the conjunction of the digital commons of knowledge and design with desktop and benchtop manufacturing technologies (from three-dimensional printers and laser cutters to low-tech tools and crafts). Two case studies are presented to illustrate three interlocked practices of this model for degrowth. It is argued that a "design global, manufacture local" model, as exemplified by these case studies, seems to arise in a significantly different political economy from that of the conventional industrial model of mass production. "Design global, manufacture local" may be seen as a platform to bridge digital and knowledge commons with existing physical infrastructures and degrowth communities, in order to achieve distributed modes of collaborative production.

1. Introduction

With the rise of new information and communication technologies, the commons,[1] i.e. shared resources where each stakeholder has an equal interest (Ostrom, 1990), received a boost (Helfrich and Bollier, 2014). Increasing access to networked computers has facilitated free cooperation and production of digital commons of knowledge and software among individuals and groups (Benkler, 2006). Initiatives such as the free encyclopedia Wikipedia and a myriad of free/open-source software projects (e.g. GNU/Linux, Apache Web Server) exemplify a new mode of information production named "commons-based peer production" (Benkler, 2006). Commons-based peer production (CBPP) is, therefore, a new way of value creation and distribution that appears within the ecosystems of commons-oriented communities, where open technological infrastructures allow individuals to communicate, self-organize and, ultimately, co-create non-rivalrous use value without the need to seek permissions (Bauwens, 2005; Benkler, 2006).

If the first wave of CBPP mainly included open knowledge and software projects (Bauwens, 2005; Benkler, 2006), the second wave seems to be moving towards open design, which is linked to the production of hardware and thus can have an impact on manufacturing (van Abel et al., 2011; Kostakis et al., 2013; Rifkin, 2014). Just as networked computers have been distributed in the population of the most advanced societies as well as of parts of emerging economies enabling people to produce and share information, the emergence of networked "makerspaces" seems to distribute the means of making (Kohtala and Hyysalo, 2015; Niaros, 2016). Such spaces can either be hackerspaces, micro-factories, fab labs or other co-working spaces which are equipped with desktop and benchtop manufacturing technologies. It should be noted that anything from three-dimensional (3D) printers or laser cutters to simple cutting tools or screwdrivers may be considered local manufacturing technologies, which enable the customized manufacturing of physical items from one's desktop or benchtop.

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[1] The notion of "commons" has been defined in manifold ways. Since this paper attempts to describe an emerging phenomenon, it embraces a broad understanding of the concept. The commons is a general term for shared resources where "no single person has exclusive control over the use and disposition of any particular resource" (Benkler, 2006, p. 61). The commons sphere may contain either rivalrous or non-rivalrous goods and resources. These have either been inherited or are man-made and may be governed by humanity as a whole or by a specific community. For example, a commons may include natural gifts, such as the air, water and land, and shared assets or creative work, like cultural and knowledge artifacts (Bollier, 2009).

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Local manufacturing technologies can use both desktop and benchtop manufacturing either separately (e.g. a spacer for asthma medications made from a plastic bottle with the help of a simple cutter tool or a plastic tape dispenser which can fully be 3D printed) or in combination (e.g., when building a new RepRap 3D printer, where 3D printed parts need to be connected via nuts and bolts). This paper adopts this concept and not similar ones, such as "personal fabrication" (Gershenfeld, 2007) or "personal manufacturing" (Bauwens et al., 2012), because the latter put the stress on the individual. Other concepts like "digital manufacturing" or "digital fabrication" (Gershenfeld, 2012; Blikstein, 2013) are too narrow, as they exclude low-technologies.

Commons-oriented makerspaces offer collaborative environments where people can meet in person, socialize and co-create (Niaros, 2016). They acquire their tools by joint contributions from their community, provide access to their machinery and resources and use inclusive forms of decision-making to manage their shared assets (Niaros, 2016; Troxler, 2011). By enriching and expanding the sphere of digital commons, these community-driven physical spaces usually operate in the "liminal zone between the monetized and non-monetized economies" (Johanisova et al., 2013, p. 15). They de-emphasize competition and promote cooperation and sharing at both immaterial and material levels, at both global and local scales (Nørgard, 2013; Niaros, 2016). A large part of the activity taking place under the CBPP umbrella presents a lot of similarities with the degrowth concept of unpaid work and decommodification (Nierling, 2012). The majority of "peers" engaged in commons-oriented projects are motivated by passion, communication, learning and enrichment (Benkler, 2006, 2011).

Kostakis et al. (2015, 2016) have only theoretically and conceptually explored the contours of an emerging productive model that builds on the convergence of the digital commons of knowledge, software and design with local manufacturing technologies. They tentatively call it "design global, manufacture local" (DGML) and argue that it could potentialize new forms of value creation. In short, DGML describes the processes through which design is developed, shared and improved as a global digital commons, whereas the actual manufacturing takes place locally through shared infrastructures with local biophysical conditions in mind (Kostakis et al., 2016). In their call for closer collaboration among degrowth and digital-commons scholars and practitioners, Kostakis et al. (2015) very briefly proposed some interlocked practices observed in DGML projects that seem to create a positive feedback loop from a degrowth perspective, especially in relation to autonomy and conviviality.

Hence, commons-based forms of peer production, such as DGML, should arguably be of particular interest to degrowth theorists and activists, because they point to alternative modes of technology governance and production that differ in scale, location, incentives and consumer-producer relationships when compared to mass production (Kohtala, 2015, p. 654; Benkler, 2011). Such governance models could catalyze cooperation, communication and sharing, allowing for more "growth in what is indeed limitless – the moral properties of our society" (Kerschner, 2010, p. 549). This article is triggered by Demaria et al.'s discussion on what degrowth is and relates to degrowth's "call for deeper democracy, applied to issues which lie outside the mainstream democratic domain, like technology" (Demaria et al., 2013, p. 209). Through two illustrative case studies, the aim is to elaborate on three interlocked practices and show how degrowth communities could use local manufacturing technologies in conjunction with digital commons. This could be considered a contribution to the plurality of legitimate perspectives towards technology (Kerschner and Ehlers, 2016).

The rest of the paper is organized as follows. Section 2 briefly presents a conceptual framework which discusses how commons-oriented technologies and local manufacturing capabilities are related to degrowth. Section 3 includes two participatory case studies in which two of the authors have been playing a key role. It is described how the interlocked practices for degrowth – as first articulated by Kostakis et al. (2015) – are manifested in the cases. Section 4 reflects on the previous sections by summarizing the connection between digital commons, local manufacturing and degrowth, stating some limitations, and providing recommendations for future research and action.

2. Conceptual framework: three interlocked practices for degrowth

CBPP is emblematic of the changing locus of some technological development from top-down institutions to grassroots communities (Benkler, 2006). Commons-oriented technologies, such as free/open-source software and open hardware, are developed through autonomous, participatory and asynchronous collaborative efforts and thus are not centrally controlled by specific owners and/or managers. They can be viewed as objects of contestation, reconstruction and democratic participation sites through which individuals and communities can influence and change technological design and meanings (Feenberg, 1999). The emergence of the DGML model is supported by such distributed productive processes and infrastructures (e.g. the Internet, free/open-source software, desktop manufacturing) and produces commons-oriented technologies which can be locally controlled. In the vein of Gorz (1983) and Illich (1973), the latter aspect is vital for democratizing decision-making and allowing people to create value in a more autonomous way. In a nutshell, DGML follows the logic that what is non-rivalrous becomes global (i.e. global commons of knowledge, design, software), and what is rivalrous (i.e. hardware) is local. With regards to DGML, Kostakis et al. (2015) have observed and tentatively described some interlocked practices which seem to create a positive feedback loop for degrowth.

The first practice is related to the non-profit-motivated design logic of commons-oriented technologies. This is caused by the fact that the locus of design within commons-oriented communities arguably removes the incentive for planned obsolescence, characteristic of a profit-maximization approach to design and engineering (Packard, 1960; Guiltinan, 2009). On one hand, proprietary design in for-profit enterprises often aims to achieve planned obsolescence in products that would wear out "prematurely" and thus maintain tension between supply and demand (Packard, 1960; Kostakis et al., 2015; Illich, 1973). This tendency is more evident in monopolies or oligopolies (Bulow, 1986; Waldman, 1993); however, there is currently no rigorous empirical evidence on practices related to planned obsolescence. On the other hand, commons-oriented design communities, such as those of Wikispeed, Wikihouse or the RepRap project, do not share the same incentives as for-profit enterprises. Nevertheless, it should be emphasized that, first, the design-embedded sustainability of DGML products currently rests on no empirical evidence (Kohtala, 2015) and, second, maker-practitioners differ in their interest to address environmental issues and might be more interested in keeping track of the rapidly evolving new technologies (Kohtala and Hyysalo, 2015). Nevertheless it seems more likely that commons-oriented makers, who mainly design in order to cover their own needs and have no incentive to design for obsolescence, would aim to design for sustainability (Kostakis et al., 2015; Kohtala, 2015).

The second practice of DGML concerns the use of local manufacturing technologies to create an on-demand production system, instead of a supply-driven one. By relocalizing production into a network of local makerspaces, a considerable amount of production costs could be removed by minimizing transportation and reducing the environmental impact of production (King et al., 2014; Kostakis et al., 2015; Kohtala and Hyysalo, 2015). In that way, knowledge tends to diffuse, while raw materials tend to travel less. There is arguably less need for spare-parts stocks, costly tools, molds or scrap requirements. Instead, use of readily available supplies, recycling of waste material in situ and minimal inventory risk become possible (Berman, 2012; Kohtala, 2015). According to Gebler et al. (2014), who performed an evaluation based on a set of three sustainability dimensions (economy, environment, society) of 3D printing, the sustainability implications concerning costs, energy and CO2 emissions show that sustainability potentials occur over the entire life cycle of 3D-printed products and can greatly lower the input and output intensities of industrial manufacturing. A similar empirical study showed that manufacturing using 3D printers improves the sustainability of plastic products by diminishing the environmental impact of manufacturing (Kreiger and Pearce, 2013). Nevertheless, one should be aware of the toxicity concerns regarding 3D printing (Drizo and Pegna, 2006; Short et al., 2015), as well as of its high energy consumption (Kohtala and Hyysalo, 2015). Further, since the DGML type of manufacturing is on-demand with the designs available through both global and local networks, not only overproduction but also the massive need to promote consumption through mass advertising and communication could be decreased. This might be of interest to proponents of strong sustainable consumption governance (Lorek and Fuchs, 2013), who see it as a precondition for moving towards degrowth. However, it should be noted that while this practice holds true for several technologies, it does not cover all. Of course, the DGML model does not offer a one-size-fits-all solution, but rather endorses adaptability according to local needs.

The third practice involves the mutualization of products and instruments of production or, in other words, the emergence of a genuine “sharing economy” in which idle resources are identified and used in mutual ways (Kostakis et al., 2015). This practice does not follow the same logic as simply selling or renting idle resources. It is about allowing several groups and individuals to benefit from the same resources in tandem. Furthermore, it allows them to utilize these resources in a non-market framework, meaning that production takes place to address specific needs rather than to offer a continuous supply of products. This can be achieved by mutualizing and sharing infrastructures, both immaterial (digital commons of knowledge, software, design) and material (e.g., makerspaces, common machinery). For instance, see the “xtreme manufacturing” approach of the Open Source Ecology and WikiSpeed projects where the use of desktop and benchtop manufacturing allows for local on-demand production in makerspaces. Individuals and communities would globally cooperate on the design of the products, the design of the machinery to produce them and even on the collaborative processes through which both the previous aspects are made possible. Moreover, this practice involves adapted legal frameworks (licenses) of ownership and governance which would enable generative forms of managing productive immaterial resources. “Generative” refers to any resource that can be used to generate more resources (Buechler, 2015). Contrary to state property, commons-based property legal regimes allow individuals to manage a resource themselves. Furthermore, it is fundamentally different from private property, where an individual or a legal entity restricts the sharing of a resource. In commons-based forms of property, communities manage directly and autonomously each resource at their disposal (Bauwens, 2005; Kostakis and Giotitsas, 2013). Commons-based licenses, such as the General Public License or forms of the Creative Commons licenses, enhance shared immaterial resources, since the more people are using a digital commons, the more valuable it becomes (Benkler, 2006). In addition, the sharing of manufacturing infrastructures (e.g. the use of a public/commons-oriented makerspace) is another generative form of physical resource.

To recap, arguably none of these practices is an automatic result of technology alone, but of a socially formatted appropriation of technology by creative communities. None of these developments could have been achieved without the sharing of knowledge and physical infrastructures, for which the existence of socialized global infrastructures, like the Internet, are of paramount importance. The next section will illustrate how these three interlocked practices are manifested within two case studies of DGML projects.

3. Case studies

In the absence of a spectrum of thoroughly examined DGML examples, this paper relies on two instrumental case studies which offer insights into this particular issue (Stake, 1995). It also adopts a participatory approach to case-study research, where case participants become contributing researchers and, hence, experts who can contribute to the understanding of the underlying processes of the issue within the contextual setting (Reilly, 2010). In particular, two of the authors have been the instigators of the selected case studies. To balance the bias and the tendency to confirm any preconceived notions, the other two authors attempted to provide critical checks.

Open-source, affordable robot hands and prosthetic devices as well as locally manufactured small wind turbines and pico-hydroelectric plants constitute the cases. They were instrumentally chosen because they exemplify the DGML model and allow us to explore how the phenomenon manifests within them (Willig, 2001). Therefore, through two illustrative case studies, this section describes how the convergence of digital commons with local manufacturing technologies can create forms of value creation of interest to degrowth. The discussion is organized around the aforementioned three interlocked practices.

3.1. Robot hands and prosthetic devices

Nowadays, the robot hands market is dominated by rigid, fully-actuated devices that are equipped with multiple actuators and sophisticated sensing elements (e.g., high-resolution encoders for the joints and tactile force sensors for the fingertips). Moreover, these hands typically require complicated control laws in order to interact with the environment or to execute robust grasping and dexterous, in-hand manipulation tasks. For these reasons, the particular hands cost between $20,000 and $100,000 (see Table 1) and require a lot of effort and expense to be repaired and maintained (McGimpsey and Bradford, 2010; Yudkoff and Dayanim, 2013).

Another important aspect of the current situation in the prosthetics market is the fact that prosthetic devices also require frequent repairs and replacements, which can only be performed by experts. For example, the expected life span of a myoelectric prosthetic arm-hand system (that costs ~$160,000) is five years, while the maintenance may include cable repairs, suspension-liner replacement, harness repair, batteries and other parts that amount

Table 1
Costs of commercially available prosthetic hands (McGimpsey and Bradford, 2010).

Device type	Cost
“Split-hook” devices	~ $10,000
Open/close cosmetically realistic myoelectric hands	$20,000–30,000
Neuroprosthetic hand systems	~ $100,000

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to 10% of the cost of each prosthesis (Yudkoff and Dayanim, 2013). The same study reports that the average annual cost of the prosthetics hardware for an upper-limb amputation exceeds $55,000. Furthermore, a recent study reports that the average lifetime cost for prosthetics and medical care for the loss of a single arm for an amputee in the USA is more than $800,000 (Blough et al., 2010). Thus, it becomes evident why most amputees express their disappointment at the large cost of buying and maintaining a prosthesis, the increased weight of the device, as well as the difficulties they face with repairs. The fear of damaging the prostheses also causes most amputees to avoid using them in everyday life tasks, instead they use simple hooks or grippers. The situation is far worse for people that are uninsured or for people that have partial insurance that does not cover modern prosthetic devices, the required repairs or maintenance costs. Moreover, in 2014 in the USA, 9.2% of the population (29 million persons) was completely uninsured (Cohen and Martinez, 2015). It must also be noted that amputees in countries that are suffering from poverty or wars do not have access even to basic health care.

All these facts were sources of inspiration for the creation of the OpenBionics project (Liarokapis et al., 2014). This initiative produces a digital commons of designs, software and knowhow for the development of anthropomorphic, underactuated, modular, adaptive, lightweight and intrinsically compliant robot and prosthetic hands of low complexity and cost (Kontoudis et al., 2015) (see Fig. 1). The design was based on a simple idea: to use steady elastomer materials (e.g., silicone or polyurethane sheets) in order to implement the human extensor-tendons counterpart and cables driven through low-friction tubes to replicate the human flexor-tendons analogues. Human-likeness of robot motion and structure is achieved by employing appropriate metrics of anthropomorphism in the design process. The use of parametric models derived from hand anthropometry studies allows for the creation of personalized devices.

The thumb mechanism can attain nine different configurations, replicating the human thumb opposition to the other fingers, with only one degree of freedom. A selectively lockable differential mechanism employs a set of simple buttons that can block the motion of each finger, allowing the user to intuitively select between 16 distinct index-, middle-, ring- and little-finger combinations. A single actuator combined with the differential mechanism can execute 144 different grasping postures and gestures, facilitating the desired cost and weight reduction. The structure of the hand is extremely robust, and especially the robot fingers can withstand significant torsional forces and impacts.

The proposed hands can be fabricated with low-cost desktop manufacturing technologies, such as 3D printing and computerized numerical control (CNC) machines, using off-the-shelf, low-cost and lightweight materials that can be easily found in hardware stores around the world (Zisimatos et al., 2014). The costs and weights of the OpenBionics robot and prosthetic hands, as well as the cost of replacing a damaged finger unit are reported in Table 2. It must be noted that the presented figures do not include research and development or tools costs. The particular prosthetic hands are as functional as the commercially available solutions (Kontoudis et al., 2015), and they cost only a fraction (i.e. 0.1–1%) of their price (McGimpsey and Bradford, 2010; Webster, 2013; Yudkoff and Dayanim, 2013). The OpenBionics robot and prosthetic hands can be created within 4–6 working hours. Although it is hard to collect the production times of other commercially available prosthetic hands, the particular amount of time is considered small and minimizes the labor cost.

The OpenBionics website (www.openbionics.org) serves as an online repository of videos, codes, designs and tutorials. A variety of designs is provided, and website visitors are able to request the files needed to develop a personalized prosthesis by filling out an appropriate form. Further, the initiative has partnered with the OpenRobotHardware.org project, which is intended to serve as a resource for efforts focusing on open-source mechanical and electrical hardware, with a particular focus on projects that may be useful in robotics applications, research and education. Thus far, the OpenBionics and the OpenRobotHardware initiatives have attracted more than 50,000 unique visitors from 157 countries and the designs have been downloaded thousands of times.

3.1.1. *Design-embedded sustainability*

The OpenBionics initiative is currently represented by the Control Systems Laboratory of the National Technical University of Athens (a public, non-profit higher education institution) and does not follow a planned obsolescence strategy. The sustainability and democratization aspects are indeed evident in the designs, as the focus is on providing robust, modular, reusable and easily maintainable solutions that will facilitate cooperation and replication by others. For example, the OpenBionics robot and prosthetic hands share the same modular finger structure, so as to enable a potential user of the devices (e.g., an amputee, a technology enthusiast, a

Table 2
The costs and weights of the OpenBionics devices (Zisimatos et al., 2014; Kontoudis et al., 2015).

Device	Cost	Weight
Robot hand	$60–100	~200 gr
Prosthetic hand	~$200	~300 gr
Modular finger unit	~$10	15–20 gr

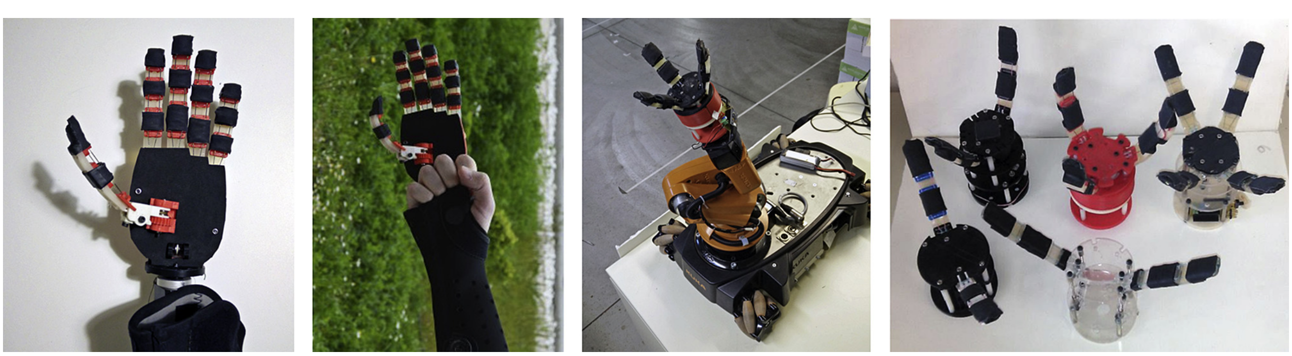

Fig. 1. The OpenBionics prosthetic and robot hands.

researcher, or even a company) to use a minimum set of tools and units (e.g., developed fingers) and devote a minimum amount of time to getting familiarized with the required construction procedures or repairing and maintaining a damaged or old device. It must be noted that the easier it is for the user to repair the prosthesis, the less likely it is that he/she will seek help from a professional/expert, minimizing the maintenance costs (all repairs can be made by a non-expert).

Moreover, as has already been mentioned, the proposed robot and prosthetic hands are significantly robust, do not require frequent repairs, and the cost of their replacement units is very low (e.g., $10 for each broken finger), when compared with the commercially available prostheses that require up to ~$17,000 annually (Yudkoff and Dayanim, 2013). In addition, the modular basis of the OpenBionics robot hands allows for the replication of multiple robot-hand models with the same wrist module. Such a basis also facilitates repairs and robot-hand maintenance, since damaged fingers can easily be replaced with new units. These hands can be used in industrial automation scenarios by companies that cannot afford robotic production-line solutions that cost hundreds of thousands or even millions of USD.

It must be noted, though, that the OpenBionics devices require for their replication certain desktop manufacturing technologies (e.g., 3D printers or laser cutters) that are not yet readily available in every house. Thus, a strategic plan of the OpenBionics initiative is to establish a global network of makerspaces where the OpenBionics designs could be built on demand or where the potential user could seek assistance for repairs. Finally, the software code that has been written for the control of the different actuators, or for data collection from the various sensing elements, is also shared among the robot and the prosthetic devices, minimizing the required development effort.

The aforementioned characteristics provide the OpenBionics devices with a strategic advantage over competitors and commercially available solutions. In 2015, the OpenBionics initiative won the Robotdalen International Innovation award and has now initiated a collaboration with Robotdalen to perform clinical trials and commercialize affordable prosthetic devices. Among the future plans of the OpenBionics initiative is the creation of a spin-off/start-up company for the commercialization of the derivative designs without compromising their open dissemination and licensing.

3.1.2. On-demand production

The OpenBionics initiative uses open designs, local makerspaces and shared desktop manufacturing equipment in order to contribute to the creation of a new on-demand production system. By relocalizing the production of the OpenBionics prosthetic hands into the aforementioned network, the transportation costs, the advertising/dissemination costs and the environmental impact of their production are minimized, since materials travel less and the required infrastructure and technical expertise is shared (King et al., 2014; Kostakis et al., 2015; Kohtala and Hyysalo, 2015). All the designs are freely available to everyone to replicate, modify and customize according to their preferences, and of course to ameliorate them, proposing derivative solutions that are aesthetically or functionally better. Moreover, the OpenBionics prosthetic hands can be personalized to meet the specific needs of each patient, or they can even be developed for specific tasks (e.g., prostheses for sport activities or for heavy duty tasks) (Kontoudis et al., 2015). All hand designs have been developed accordingly to allow their replication by non-experts. This demand-driven production paradigm accelerates innovation and leads to advanced, personalized prosthetics that cost a fraction of the price of the currently commercially available solutions, requiring also lower maintenance costs.

3.1.3. Sharing

As said, OpenBionics has a global-commons orientation in sharing its designs, software and know-how. In this respect, the initiative has initiated international cooperation with various commons-oriented makerspaces and maker communities through participation in related conferences, exhibitions and competitions and through the organization of workshops and seminars. These communities are often based on open spaces of cooperation and innovation and range from hackerspaces to fab labs and creativity studios. The motivation behind these spaces is that everyone can take advantage or contribute to the shared infrastructure (e.g., 3D printers, laser cutters, CNC machines, PC systems, sound and photo studios), facilitating a mutualization of the means of production and propelling the emergence of a genuine “sharing economy” with more and direct human connections (Helfrich and Bollier, 2014). For example, in order to develop the required hand electronics (e.g. printed circuit boards), the OpenBionics initiative used the infrastructure of the Greece-based Athens Hackerspace.gr, a physical space dedicated to creative code and hardware hacking. For research purposes and for the development of the OpenBionics devices, the team uses the infrastructure of the Control Systems Laboratory of the National Technical University of Athens. The OpenBionics research was initially supported by the European Commission with the Integrated Project no. 248587, “THE Hand Embodied”, within the FP7-ICT-2009-4-2-1 program “Cognitive Systems and Robotics” (€560,000, 2010-14).

The OpenBionics designs are available under a Creative Commons license that allows people to share, copy and redistribute the related material in any medium or format and adapt, remix, transform and build upon the material for any purpose (even for commercial purposes). Such a license was selected in order to empower grassroots innovation, since the more people that modify and work on the OpenBionics hand designs, the more efficient and dexterous they arguably become. Through their participation in the Hackaday.io and other commons-oriented communities, the OpenBionics team members have supported the replication of their prosthetic and robotic hand designs by others, while many different groups around the world have started working on derivative versions of the designs that maintain the same commons-oriented license. For example, the robot and prosthetic hands' GitHub repositories of the OpenBionics initiative have been copied/forked numerous times, enabling new users to freely experiment with the provided designs and create new customized versions. Moreover, the OpenBionics designs have been acquired by a community of researchers, makers, hobbyists and professionals currently spread over 174 countries and 7500 cities around the world.

All the OpenBionics designs were initially developed by a cross-institutional team of roboticists but are nowadays maintained and modified by a community of makers, researchers and hobbyists. More precisely, the OpenBionics team initially focuses on the preparation and prototyping of new innovative designs using their expertise in robot-hand design, robot grasping and manipulation and brain-machine interfaces. The prototypes are thoroughly tested with extensive experimental paradigms, and their CAD files are openly distributed through appropriate dissemination channels (e.g., GitHub repository). Furthermore, the CAD files are supplemented with comprehensive tutorials that allow the replication of the proposed designs by non-experts. Subsequently, the worldwide community of makers, researchers, hobbyists and hardware hackers provides feedback on the proposed solutions, modifies the designs, proposes new solutions and possible alternatives and develops derivative versions. Thus, progress and innovation can be accelerated via a synergistic cooperation of experts and non-experts.

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3.2. *Small wind turbines and pico-hydroelectric plants*

Small-scale off-grid renewable energy systems, frequently encountered in rural households or village communities, can utilize devices like solar panels, hydroelectric plants and small wind turbines depending on the resource mix of the area (Patel and Chowdhury, 2015). Although a well-sited small wind or hydroelectric turbine may produce much more energy than a solar panel of the same rated power (Kabalan and Anabaraonye, 2014), these technologies have higher capital costs, require significantly more maintenance due to their moving parts (Kuhn, 2010) and at some point in their lifetime will require the replacement of a component, which might often be difficult to obtain (Leary et al., 2012a, 2012b; Ferrer-Marti et al., 2010). Locally manufactured small wind turbines and pico-hydroelectric plants aim to address such issues by deploying an alternative process of designing and manufacturing, based on the engagement of the end users and the support of relevant community networks.

Hugh Piggott, a widely acknowledged expert in small wind energy, has been living in the remote off-grid community of Scoraig in Scotland since the mid-1970s. He started experimenting with household wind-energy systems manufactured from parts that could be salvaged from the scrapyard of the nearest town. Gradually he developed a design which could be locally manufactured with simple benchtop tools and techniques, using mostly locally sourced materials. Piggott documented the efficient wind turbine designs he had developed and their manufacturing techniques in a construction book manual (Piggott, 2008) that describes the manufacturing process of six small wind turbines of rotor diameters from 1.2 m to 4.2 m (with rated power of 200 W and 3 kW respectively). The construction of such a wind turbine requires a group of five to eight people, without previous experience, to work for about five days to manufacture it from scratch. The wind turbine blades are made out of local varieties of "softwood", which are hand carved with basic woodworking tools. The axial flux permanent magnet generator has a unique disk topology which facilitates simple manufacturing of the stator windings and the rotor magnet disks, while the wind turbine's moving parts are mounted on the wheel-bearing hub of a car that can be recycled from an old vehicle (Piggott, 2008; Bartman and Fink, 2008; Latoufis, 2012). All materials used in the manufacturing of the wind turbines can be found in the local markets of most medium-sized towns, apart from the magnets, which need to be ordered from specialized online dealers.

The performance characteristics of locally manufactured small wind turbines, such as power curve, annual energy production and wind-electric system efficiency, have been monitored and found to be similar or better when compared to commercial small wind turbines available on the global market (Latoufis et al., 2015a; Sumanik-Leary et al., 2013; Mishnaevsky et al., 2011). The total cost of manufacturing and installing a wind turbine with a 2.4 m rotor diameter (Fig. 2) would amount to $1700 (including the tower, foundations and electronics) (Latoufis et al., 2015a). This is a 65% reduction in the purchase cost when compared to a commercial wind turbine system of the same status supplied from a low-cost but trustworthy manufacturer (Christensen, 2012).

Additionally, when the net present cost of a locally manufactured small wind turbine and a commercial equivalent are compared (Fig. 3), it is found that locally manufactured technology can offer savings of 20% over the lifespan of the system (Sumanik-Leary et al., 2013). Similarly, the locally manufactured small wind turbine has a significantly lower electricity cost than the commercial turbine, with a Levelized Cost of Energy at 0.95$/kWh, as opposed to 1.23$/kWh of the commercial equivalent (Sumanik-Leary et al., 2013). Since locally manufactured small wind turbines can be manufactured by non-experts during training courses, labor costs expressed in monetary terms are usually non-existent, thus enabling low income communities to access this technology. Furthermore, the locally manufactured small wind turbine produces more power at lower wind speeds, which are more frequent in most sites, consequently making this turbine more compatible with the energy demand of an off-grid system (Sumanik-Leary et al., 2013; Latoufis et al., 2015a).

Fig. 2. A locally manufactured small wind turbine of rated power 600 W at 10 m/s, able to produce energy of 1270 kW h/year at a 5 m/s mean wind-speed location.

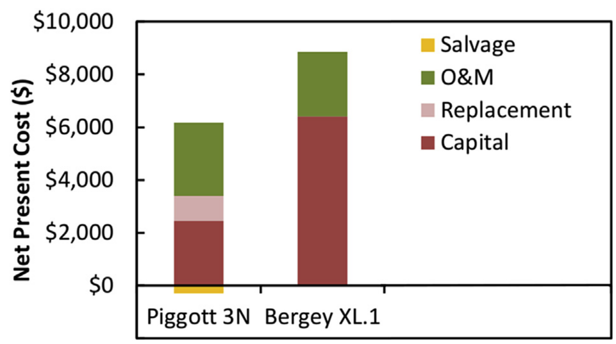

Fig. 3. Net present cost by system component with a used discount rate of 10% (O&M stands for Operation & Maintenance; Piggott 3N is a locally manufactured small wind turbine; Bergey XL.1 is a commercial small wind turbine) (Sumanik-Leary et al., 2013, p. 5).

Piggott's (2005) open-source designs have propelled the creation of a global network of designers, manufacturers and users of locally manufactured small wind turbines. One such group is Nea Guinea, a Greece-based non-profit organization interested in community resilience and self-sufficiency. The renewable energy workshop of Nea Guinea started building locally manufactured small wind turbines with the aim to provide the back-to-the-land movement in Greece with appropriate knowledge and tools to achieve a transition to a more sustainable lifestyle (Latoufis, 2014). Addressing the need of some of these farmers for inexpensive electricity production from pico-hydroelectric plants, Nea Guinea has developed a 500 W pico-hydroelectric plant (Fig. 4) for off-grid systems in cooperation with the Rural Electrification Research Group (RurERG) of the National Technical University of Athens. The latter uses Piggott's (2008) designs for manufacturing the generator, and the openly accessible designs for locally manufactured

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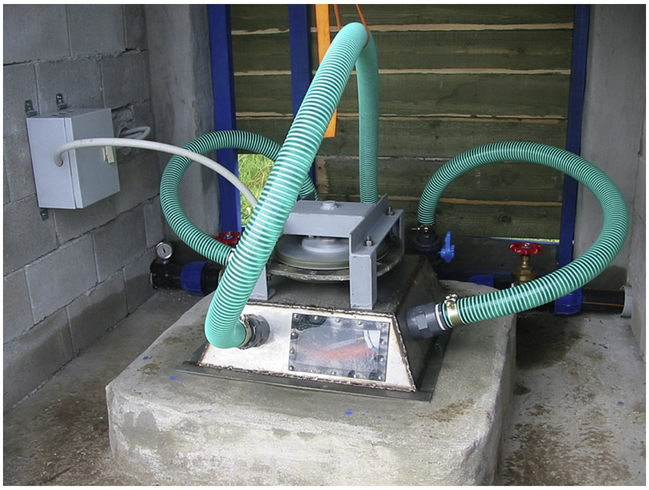

Fig. 4. A 500 W locally manufactured pico-hydroelectric plant.

pico-hydroelectric casings and low-cost turgo runners of Joseph Hartvigsen (Cobb, 2011).

A prototype has successfully been in operation in a rural farm in Greece for the past three years without the requirement of any maintenance or spare parts. The hydroelectric plant uses 20 m of head and 5 l/s flow to produce enough electricity to supply the farmhouse with hot water for bathroom/kitchen use and enough energy for refrigeration, lighting, power tools, communications and a washing machine. So the hydroelectric plant satisfies all energy needs of the residents apart from cooking, for which they use natural gas, and heating, for which they use biomass. Compared to other commercial products of the same power rating (PowerSpout, 2014), the total cost of this hydroelectric plant has been reduced by 50%. Currently there is promising experimentation with 3D printers and the use of recycled plastics for locally manufacturing the turgo runner.

3.2.1. Design-embedded sustainability

Well-sited pico-hydroelectric plants and small wind turbines for off-grid systems, such as the ones described earlier, can produce more than 60 MW h and 20 MW h of electricity, respectively, in their lifetime (typically 15 years). So they can reduce significantly, if not eliminate, the use of a diesel engine, thus reducing greenhouse gas emissions (Fleck and Huot, 2009). Locally manufacturable designs aim at making such technologies accessible to remote rural communities by reducing the initial investment as well as future maintenance costs. Through the active engagement of the users in the manufacturing and maintenance of the machines, significant reductions of costs and emissions are achieved in the transportation of materials, as well as labor costs for manufacturing and maintenance, which would otherwise be charged by commercial manufacturers and installers of renewable energy systems (Sumanik-Leary et al., 2013). In addition, expenses are spread out more evenly over the lifetime of a locally manufactured machine, contrary to the high upfront cost of commercial ones, thus making them more accessible to low-income social groups, such as rural communities (Sumanik-Leary et al., 2013). It must be noted, though, that as locally manufacturable designs depend on the active participation of the user in observing the operation of the machines and in performing maintenance on time, the inability of the user to follow this process may lead to failures. As locally manufactured turbines will require more frequent preemptive maintenance, for example once a year, than other high-standard commercial turbines, the appropriate engagement of the user is a crucial aspect for such technologies.

Locally manufactured pico-hydroelectric plants and small wind turbines are designed to increase reliability in energy production, simplicity of operation and maintenance and ease of replication. This is achieved through a reductive design approach which aims to simplify and reduce the number of components in order to avoid complexity and the likelihood of failure, while increasing performance and reliability. Commercial products are not always able to follow such design approaches as they might seem crude – which makes advertising or promoting a product difficult – or may not conform to specific market requirements (Gipe, 2004). An example of this is the use of the pipe-in-pipe joint for the furling and yawing mechanisms of a locally manufactured small wind turbine, which avoids the ball bearings, slip rings and brushes used by commercial manufacturers. Furthermore, the lifetime of locally manufactured machines can be increased with the continuous replacement of components built on site. On the other hand, commercial products depend on the ability of the manufacturer to remain in business, with many examples of large commercial small-wind-turbine manufactures going out of business in recent years and no longer supporting their customers with spare parts (IREC, 2013).

Reliable operation is achieved not only through a robust and efficient design, but also through a highly reconfigurable design. This is achieved with the frequent upgrading of the construction manuals with many derivative designs adapted to local conditions; their translation into different languages; and the development of appropriate technology-transfer practices, based on the experience of manufacturers and users in different parts of the world. In order to organize this common pool of knowledge, a grassroots technological network of practitioners provides the necessary human resources on a voluntary basis. WindEmpowerment.org, a registered charity in the UK with more than 40 member organizations spanning most continents, and all the local fora of wind-turbine builders provide a continuous online support and development network. This network can help anyone to troubleshoot problems related to maintenance or design reconfiguration according to local environmental conditions. In addition, the network intends to address problems that its members might face due to language or cultural barriers, lack of Internet access, lack of adequate technical know-how from the end user's side or lack of locally available materials.

Finally, in case of failure, the functional parts of the machine can be reused after some maintenance, and there is no need to replace the whole set of components, as happens with the majority of commercial products. For example, when a composite fiber-glass small-wind-turbine blade is damaged, it is common practice to replace the complete blade instead of repairing it, as the tools and technicians required are not available locally or the part is mass-produced and no repair process has been planned. Similarly, in commercial pico-hydro generators, if a magnet corrodes, it is not possible to replace it, as the replacement part consists of the complete rotor with all magnets mounted (PowerSpout, 2014). On the other hand, wind-turbine blades are carved out of wood and can be functional for decades with simple maintenance. Corroded magnets of wind and pico-hydro generators can individually be replaced, or designs can be reconfigured to allow the use of locally available magnet dimensions if a specific replacement cannot be sourced in the market. In the case of pico-hydro turbines, defective cups of the runner can be manufactured with a 3D printer using recycled plastics. Finally, reusing functional parts after some maintenance can reduce international air transportation of goods and delivery times for small-wind-turbine replacement parts (Kuhn, 2010). It must be noted, though, that the performance of good-quality maintenance or the repair of a failure can depend on the level of technical knowledge or manual ability of the user, which might be lacking at the time and will need to be gradually strengthened with the technical support of the local organization of the global network.

3.2.2. On-demand production

Locally manufactured small-wind-turbine production occurs through a construction course, where people engage with the turbines and the social support networks around them. The labor process for the course participants is not characterized by specialization and intensification but instead can be described as a process of volunteering and participating in a learning process. The wind turbines are usually manufactured in a local workshop with the assistance of a local organization which regionally represents the network and enables an appropriate engagement with regional cultural contexts and language. It is the goal of this organization to gradually disseminate the technology on a regional level by increasing the manufacturing capability of other workshops and thus decentralizing the technology. There are, of course, cases where the users create a dependency on the local organization and are slow in building on their own manufacturing capacity and knowledge base for performing maintenance.

In most cases, the turbines are built on demand with a specific installation in mind. Their open designs can be adapted to the community's energy requirements, the availability of natural resources and the local environmental conditions. The wind turbines can be manufactured for renewable energy systems of different voltages and can be reconfigured to suit already existing systems. In addition, such wind turbines and pico-hydroelectric plants can be manufactured using reused parts, desktop manufacturing technologies and can be adapted to locally available materials. The generator design itself is modular and can be reconfigured for use in wind, hydroelectric or pedal-power custom applications, which require a wide range of rotational speeds. This is not possible with off-the-shelf machines, as they produce their rated power at specific rotational speeds and their stator windings cannot be easily reconfigured to accommodate such variations. Assistance on such modifications is provided by available manuals on specific topics and practitioners through relevant digital fora.

A practical example of such activities are the locally manufactured small wind and pico-hydro projects performed by Nea Guinea in Greece. Three small wind turbines and one pico-hydro plant have been manufactured on demand for different projects with the participation of the end users. A grid-connected 1.8 m-rotor-diameter small wind turbine was constructed as a student project in collaboration with the National Technical University of Athens, which involved the reconfiguration of the generator in order to comply with a specific grid-tied inverter. The wind turbine was installed in the environmental summer camp of “Meltemi” in the outskirts of Athens as part of a pilot mini-grid. A battery-connected 3 m-rotor-diameter small wind turbine was manufactured in the workshop of Nea Guinea in Athens as part of an adult-education course and was installed in an already existing off-grid renewable-energy system in the eco-community of “Spithari” in Marathonas, after reconfiguring the generator to the appropriate battery voltage. An AC-coupled 2.4 m-rotor-diameter small wind turbine was manufactured in Athens in order to be installed in an organic olive farm in Filiatra as part of an off-grid hybrid system. The generator was reconfigured to operate with the grid-tied inverter used in the system, and the wind turbine rotor was sized according to the mean wind speed of the area. The small wind turbine was once again manufactured as part of a training course for adults in the Nea Guinea workshop. Finally, a pico-hydro plant was designed for a permaculture mountain farm, as the wind and solar resource in the area were not adequate, while the hydro resource was abundant. The wind-turbine generator was reconfigured to operate with a turgo runner for direct battery charging. The pico-hydro plant was initially part of a student project in collaboration with the National Technical University of Athens and a derivative of that design was manufactured in the Nea Guinea workshop as part of a practical adult-education course and then installed on the farm.

3.2.3. Sharing

Piggott's (2005) designs, which have catalyzed the creation of this community-based technological network, are not patented and can be modified, improved and/or replicated by anyone and for any use. Moreover, the manufacturing process of six small wind turbines is described in his low-cost book manual (Piggott, 2008), while digital copies are available on a donation basis. A derivative design based on Piggott's manufacturing plans is the book manual of Otherpower from the US (Bartman and Fink, 2008), which describes a similar manufacturing and design process, but with modifications for more demanding environments. The designs developed by Otherpower are also shared with the Wind Empowerment network and other users through their website and online forum (Fieldlines.com).

All the organizations belonging to the Wind Empowerment network have their own local workshops, which are often open to the public for certain periods of time. During the educational construction courses held in these workshops, wind and hydro turbines are built on the demand of a user community, which provides the necessary funds for purchasing the materials. The end product is installed in the user community and is owned by them. For example, in the workshops of Nea Guinea, one can order a wind turbine by providing the funds for the materials, and it will then be manufactured during the next course. In this way, a global network of workshops can manufacture small wind turbines on demand with the assistance of local organizations representing the network. This creates a network of spaces where the technology is advanced and better adapted to the local context. Furthermore new knowledge is generated and then shared on relevant online fora, network events, online seminars and conferences. There are cases, however, when practical courses are held and small wind turbines are built without a specific installation in mind, as it is important to share the manufacturing knowledge and expand the network. Yet, this can create a surplus of small wind turbines which have no place to be installed, and in this case the local organization creates a campaign to find a “home” for these turbines.

In addition, the various educational approaches and scenarios are shared through common projects in countries of the global South, where member organizations team up to execute a rural electrification project in a selected region with the aim of creating a regional group. A recent example of such joint educational activities is the Wind Empowerment project in Ethiopia (Latoufis et al., 2015b), where V3 Power from the UK, Nea Guinea from Greece and I-Love-Windpower from Tanzania organized training courses in the Somali and Afar regions, in collaboration with the local NGO Mercy Crops. The aim was to train students of local technical colleges, some previously trained as metalsmiths, carpenters or electricians, on wind energy and locally manufactured small wind turbines. The turbines constructed were successfully installed in rural communities in the region and are closely followed up with the support of the Wind Empowerment network. This takes place through the use of an open-access guide for the maintenance and service of locally manufactured small wind turbines (Wind Empowerment, 2015) and the support of the local NGO that facilitates the process.

In terms of licenses, although the design manuals are technically open-source, they are not available under a particular commons-oriented license. The hardware itself is not patented, so anyone can build and modify the designs, which are in public domain. The level of awareness around the digital-commons discourse has been

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low within the global network interested in such technologies. It might be argued that the lack of an officially adopted commons-oriented legal framework does not mind engineers and hobbyists who already can freely experiment with the designs and build functional turbines without having to pay patent license fees. At the same time, modifications would be shared through online and offline fora and relevant manuals. However, several emerging commons-oriented hardware projects, which explicitly promote commons-based forms of property (such as the CERN or TAPR open-hardware licenses), have been triggering discussions among an increasing number of engineers and makers. It is currently an open question as to how a collective design and piece of hardware could be produced by the Wind Empowerment network and under what license it could explicitly be provided.

4. Conclusions

In a plurality of legitimate perspectives towards technology, this article attempts to shed light on a specific option and show why the DGML model of production should be of interest to the degrowth community of scholars and practitioners. Two illustrative case studies provide a preliminary understanding of the positive dynamics of three interlocked practices for degrowth: the incentives for design-embedded sustainability, the possibilities of on-demand production and the practices of sharing digital and physical productive infrastructures. It is thus concluded that DGML points to non-negligible tendencies that may separate it from the conventional industrial model of mass production, in terms of scale, location, incentives and collaborative practices.

A limitation of this paper is that the criticisms and problems of two main pillars of the DGML model, i.e. information and communication as well as desktop manufacturing technologies, have not been directly addressed. Those criticisms and problems may pertain to resource extraction, exploitative labor, energy use, planned obsolescence or material flows. For a rigorous academic treatment of the topic, a thorough evaluation of DGML products and practices would need to take place from an ecological-economics perspective (e.g. life-cycle assessment). Moreover, it would be important to study the degree to which the users of a DGML product feel in control of the technology and knowledge necessary for its use and manipulation.

The pertinent question may not be whether degrowth should be wary of technology, in both its development and use. Instead, the question could be posed as follows: what technology, and for whom? An evidence-based understanding of the transitional dynamics of new forms of use-value creation, enabled by modern technological capabilities and the reemergence of commons, is necessary in order to advance their integration into a coherent mode of production in the spirit of degrowth. This may allow us to bridge commons-oriented practices with existing physical infrastructures and degrowth communities, while tracing cooperation amongst diverse stakeholders, distributing the means of making and, thus, democratizing technological development. Hopefully this article will serve as trigger for such a discussion and exploration.

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