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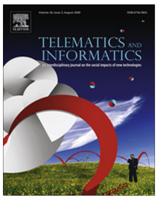

Commons-based peer production and digital fabrication: The case of a RepRap-based, Lego-built 3D printing-milling machine [☆]

Vasilis Kostakis [a,*,1], Marios Papachristou [b,2]

[a] Tallinn University of Technology, Akadeemia Tee 3, 12618 Tallinn, Estonia
[b] P2P Lab, Ioannina, Greece

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ABSTRACT

Through the case of the RepRap-based, Lego-built three-dimensional (3D) printing-milling machine, this paper sets out to discuss and illustrate two points: First, on a theoretical level, that modularity, not only in terms of development process but also of hardware components, can catalyze Commons-based peer production's (CBPP) replication for tangible products enabling social experimentation and learning. Second, the hybrid 3D printing-milling machine demonstrates the digitization of material and the potential of digital fabrication. We show how the synergy of a globally accessible knowledge Commons as well as of the CBPP practices with digital fabrication technologies, which are advancing and becoming more and more accessible, can arguably offer the ability to think globally and produce locally.

1. Introduction

Plenty of attention has been gathering around the information production models enabled by the modern information and communication technologies (ICT) and brought to the forefront by collaborative projects such as the free/open source software (FOSS) movement or the free encyclopedia Wikipedia. On the other hand, authors, such as Webster (2002a, 2002b), have argued against the idea of an 'information society'. They emphasize the continuities of the current age with former capitalist-oriented social and economic arrangements (Schiller, 1981, 1984, 1996; Webster 2002a,b). Kumar (1995: 154) maintains that the information explosion 'has not produced a radical shift in the way industrial societies are organized' to conclude that 'the imperatives of profit, power and control seem as predominant now as they have ever been in the history of capitalist industrialism'. The widespread adoption of ICT cannot automatically produce a better world for humanity: Some technologies need the appropriate social environments to be structured in a certain way (Winner, 1986). For instance, that could be one reason why in the past decades attempts for more autonomous forms of production based on novel technologies – from the 'small-is-beautiful-experiments' (Winner, 1986) to the development of wind power from below in the 1970s (Glover, 2006) – proved unsuccessful. The case of the RepRap-based, Lego-built 3D printing-milling machine, with regard to Winner's and Glover's concerns, attempts to show that new means of production, such as the ICT and

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[*] Corresponding author.
E-mail address: kostakis.b@gmail.com (V. Kostakis).

[1] Vasilis Kostakis (PhD, MSc, MA) is currently a research fellow at the Tallinn University of Technology and a collaborator of the P2P Foundation. He is the founder of the P2P Lab.

[2] Marios Papachristou (born in 1997) is a high school student, interested in open source technologies. He is a collaborator of the P2P Lab.

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the emerging digital fabrication capabilities, could create the appropriate knowledge-based social environments and make possible not only the independent production of information but also the independent production of modular hardware, even in such an infancy form.

Through several cases of successful networked-based, collaborative projects such as FOSS or Wikipedia, some see the emergence of new 'technological-economic feasibility spaces' for social practice (Benkler, 2006: 31). These feasibility spaces arguably include different social and economic arrangements, in contrast to what Kumar and Webster claim, where profit, power, and control do not seem as predominant as they have been in the history of modern capitalism. In this technological-economic feasibility spaces a new social productive model, i.e., Commons-based peer production (CBPP), is emerging different from the industrial one. CBPP, exemplified by various software (GNU, the Linux kernel, KDE) and content (Wikipedia) projects, makes information sharing more important than the value of proprietary strategies and allows for large-scale information production efforts (Benkler, 2006). In this context, CBPP could be considered an early seed form stage of a new mode of information production enabled through Internet-based coordination where decisions arise from the free engagement and cooperation of the people, who coalesce to create common value without recourse to monetary compensation as key motivating factor (Bauwens, 2005; Orsi, 2009; Kostakis, 2013).

So far CBPP practices have been a subject to systematic research for productive fields of information such as software, news, knowledge, design and literature (Benkler, 2006, 2011; Bauwens, 2005, 2009; Bruns, 2008; Weber, 2004; van Abel et al. 2011; Kostakis and Drechsler, in press). However, only a few studies (for instance Siefkes, 2007; Carson, 2010; Troxler, 2011; Kostakis, Fountouklis and Drechsler, 2013) have dealt with the transferability of CBPP's processes to physical manufacturing. In addition, most of the scholars seem to agree that one of the key conditions for CBPP to emerge, either in the immaterial or material sphere of production, is modularity in the development processes.

This paper attempts to examine the feasibility of CBPP's expansion into physical manufacturing focusing on digital fabrication technologies and the possibility for modular design in hardware components as well. Our discussion is tentative and illustrative, built on the project of a Lego-built three-dimensional (3D) printing-milling machine, and, thus, an all-inclusive instantiation is out of scope. We begin with a brief outline of the theoretical background concerning CBPP addressing its conjunction with desktop and digital manufacturing capabilities. Next, we present the case study of our hybrid 3D printing-milling machine, a project run by one of this paper's authors. We then discuss the results in relation to the potential of CBPP's transferability to physical manufacturing, with particular reference to hardware components' modularity.

2. Theoretical background

2.1. Commons-based peer production and modularity

CBPP projects produce use value, i.e. an informational good (e.g. software, design, cultural content) free to use, modify and redistribute, part of the knowledge or cultural Commons. In addition, CBPP's development processes are based on the self-selection of tasks by the participants, who cooperate voluntarily on an equal footing (as peers) in order to reach a common goal. It has been claimed (see only Benkler, 2006; Bauwens, 2005; Tapscott and Williams, 2006; Dafermos and Söderberg, 2009) that modularity is a key condition for CBPP to emerge: 'Described in technical terms, modularity is a form of task decomposition. It is used to separate the work of different groups of developers, creating, in effect, related yet separate sub-projects' (Dafermos and Söderberg, 2009: 61). Torvalds (1999), the instigator of the Linux project, maintains that the Linux kernel development model requires modularity, because in that way people can work in parallel. Empirical research (see only MacCormack et al., 2007; Dafermos, 2013) shows that modular design is characteristic not just of Linux but of the FOSS development model in general. 'The Unix philosophy of providing lots of small specialized tools that can be combined in versatile ways', Carson (2010: 208) writes, 'is probably the oldest expression in software of this modular style'. We also observe the same approach in the development of one of the most prominent CBPP projects, that of the free encyclopedia Wikipedia. Articles (i.e., modules), which are consisted of sections (i.e., sub-modules), are built upon other articles and entries produced and, thus, can be used individually as well as in combination.

Therefore, by breaking up the raw elements into smaller modules there is both an abundance of options in terms of remixing them as well as a low participation threshold, since the individuals can have access to the modules, rather than centralized forms of capital (Bauwens, 2005; Carson, 2010). So, in theory, we can assume that if physical objects could be designed to be modular – i.e., consisted of several interchangeable parts that could be swapped in or out without influencing the performance of the rest –, then individuals could engage in production processes of collaborative designing and manufacturing (Tapscott and Williams, 2006). If the interconnected personal computers are considered fundamental means of information production whose democratization gave rise to CBPP, then what could our expectations be if digital fabrication and desktop manufacturing technologies, such as 3D printing, follow a similar path?

2.2. Desktop manufacturing and digital fabrication

The conjunction of CBPP practices with desktop manufacturing capabilities, which themselves can be products of CBPP (see, for instance, the RepRap 3D printer), can arguably give us the chance to (co-)design globally – taking from and contributing to a knowledge Commons – and produce locally responding to certain needs (Kostakis, 2013; Kostakis, Fountouklis and

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Drechsler, 2013). Further, some (see only The Economist, 2011, 2012; Rifkin, 2011; Anderson, 2012) have claimed that 3D printers, laser cutters and other desktop manufacturing technologies are leading to a third industrial revolution.

However, Neil Gershenfeld (2007, 2012), who is the head of MIT's Center for Bits and Atoms, notices that the real revolution will be in the programmability of fabrication to the physical world. An interesting comparison, which Gershenfeld (2012) points out, is the performance of a child assembling Lego and a typical 3D printer. In 3D printing a certain object is created by the building up of multiple patterned layers based on a 3D model (Hiller et al., 2011). There are many types of 3D printing, for example laser sintering, stereolithography, electron beam melting and fused deposition modeling (Hiller et al., 2011). Gershenfeld (2012) argues that the child's assembly of Lego can be more accurate than the child's motor skills would allow, because the pieces fit together intuitively since they are designed to snap in alignment: the bricks enforce constraint and, thus, accuracy. For Gershenfeld (2012), Lego exemplifies the digitization of material celebrating modular design, while conventional 3D printing represents just an analogue process, which often accumulates errors, based on digital files. 'In comparison to traditional (analog) 3D printing in which material is deposited or solidified in an inherent continuum', Hiller and Lipson state (2009:137), the digitization of material imposes finite resolution: 'the size of a single unit'.

Therefore, Gershenfeld (2007, 2012) proposes a different approach to 3D printing, viewing fabrication as a digital rather than a continuous process. An adjunct to the idea of 3D printing is investigated and tested based on the concept of "voxel" (Hiller and Lipson, 2009; Hiller et al., 2011; Lipson and Kurman, 2013). According to Lipson and Kurman (2013: 16):

> A voxel is the physical equivalent of a pixel. Voxels could be tiny, discrete pieces of a solid material. Or voxels could be tiny containers that hold whatever you put into them. (...) Objects made of voxels offer an alternative to the analog materials that comprise most physical things. If you can make something from voxels, you're one step closer to making it behave more like a programmable object, to controlling its behavior. Control over material composition of physical objects opens the door to the next stage, control over the behavior of physical objects.

Hence, any object (module) that has modularity and repeatability in its use to render a larger unit can be considered a voxel. The modularity enabled by voxels can help us create objects with completely different material properties such as strength, flexibility and/or functionality (Hiller and Lipson, 2009).

'The key to scaling up the complexity of microsystems', Hiller, Miller, and Lipson write (2011: 1094), 'lies in modularizing material and function, which requires standardizing the interface between components'. So, this way the fabrication of each module type can successfully take place in independent optimized processes and then combined into a functional hybrid system (Hiller et al., 2011). 'This enables materials and functions that would otherwise be mutually incompatible to be combined in a single integrated system', Hiller, Miller, and Lipson (2011: 1094) conclude. A standardized library of voxels with compatible geometry is envisioned, which will be manufactured in several different ways, depending on the geometry, material and size (Hiller and Lipson, 2009; Hiller et al., 2011). However, it may be most economical to mass produce the voxels since the voxel manufacturing techniques are highly specialized processes (Hiller and Lipson, 2009). Hiller and Lipson (2009) highlight that the idea of central manufacturing and distributed assembly is obvious in Lego products as modular structural components. They (2009: 147) speculate that 'as long as the function of each voxel is elementary, there will be a finite (and likely small) number of voxel types required to build arbitrarily complex objects. The end-user would order voxels of many different materials and functions.'

To sum up, we see that the voxel-based approach introduces modularity in hardware components digitizing desktop manufacturing and arguably enhancing its capabilities. Through our case study we will try to show how it can assist individuals to engage in production processes of collaborative designing and manufacturing. According to all the bibliographical resources cited above, Lego represents a typical, illustrative case of the voxel-based approach to physical manufacturing. Of course, one of the biggest challenges of digital fabrication concerns the processing of large numbers of voxels fast and accurately (Hiller and Lipson, 2009; Lipson and Kurman, 2013). In that way, eventually, it will be possible to print conductors within nonconductors, or in other words to move from 'printing passive single-material parts to printing active, multimaterial integrated systems' (Lipson and Kurman, 2013:272). It is evident that since we will have the ability to print in voxel-based 3D printers physical things that contain the intelligence of digital things (Lipson and Kurman, 2013; Gershenfeld, 2007, 2012), the role of knowledge and design becomes even more important. And therefore, the conjunction of CBPP with digital fabrication arguably reaches a new plateau concerning the ability, in Gershenfeld's words (2007, 2012), 'to think global and produce local'.

3. The RepRap-based, Lego-built 3D printing-milling machine: a case study

3.1. Introduction to the case

The synergy of a globally accessible knowledge Commons as well as of the CBPP practices, constantly enriching and expanding it, with digital fabrication technologies, which are becoming more and more accessible, can arguably offer the chance to think globally but produce locally responding to local needs. This brings to mind Schumacher's (2011: 21) articulation concerning the characteristics of the necessary methods and equipment (later called "appropriate technology", see Hazeltine and Bull, 1998) for a sustainable world: 'cheap enough so that they are accessible to virtually everyone; suitable for small-scale application; and compatible with man's need for creativity'.

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To begin with, this 'man's need for creativity' is exemplified by the case of the RepRap-based, Lego-built 3D printing-milling machine, a project initiated by one of this paper's authors, who had never seen a RepRap in the flesh. Moreover, this project reflects two more aforementioned characteristics, i.e., it can be suitable for small-scale application and accessible to the masses. Its goal is to illustrate the potential of CBPP's conjunction with desktop and digital manufacturing techniques and stress its value for learning and innovation. It aims to demonstrate that it is possible for someone with partial, if not zero, initial knowledge to instigate a similar, complex project based on an interesting idea, and to succeed in materializing it through collaboration with Commons-oriented communities, while using peer produced products and tools. In that way, it could be argued that, not only the costs would dwindle but also the initial idea of the project could advance through social production processes.

The development of a hybrid 3D printing-milling machine was initially launched in January 2012, by creating a Google Code project webpage where one would find the related information (i.e. mission, code, designs etc.) with an open call for collaboration. While components of 3D printers and computer numerical control (CNC) machines, like milling machines, were mainly metallic, wooden, and plastic – being, besides, fixed, videlicet non-adjustable ones – the idea of building a hybrid 3D printing-milling machine began incubating. 'Why don't we use Lego to build it?', was the spark to start the project. Or put differently: is it possible for someone to build sophisticated machines taking advantage of the CBPP knowledge and tools as well as of the modularity Lego components offer engaging in voxel-based manufacturing?

Immediately, the inspiration came through the RepRap 3D printer, one of the most prominent CBPP hardware projects, whose designs are openly accessible under a Commons-oriented license. Furthermore, the RepRap project has a large, international community of enthusiasts supporting relative developments. Benefiting from RepRap's open designs and knowledge, we attempted to create, from scratch, a functional hybrid machine, almost entirely using Lego, which would be open to further social experimentation. Moreover, we tried to use solely FOSS and open hardware, reducing production costs and shifting towards knowledge sharing. The issues that are about to be discussed below have firstly to do with our project's design and fabrication phases with the aim to shed light on the collaborative and learning-by-doing processes. Next, based on this experience, we discuss the significance of open designs and modularity for localized social production, innovation and learning.

3.2. Design and fabrication

The first step was to understand how a low-cost 3D printer works and, therefore, we begun studying the designs of the RepRap 3D printers[3]. The RepRap (short for replicating rapid prototyper) project is an initiative with the aim to develop an accessible 3D printer that can print most of its own components (Jones et al., 2011). RepRap uses a variant of fused deposition modeling, an additive manufacturing technique, and prints objects from ABS, PLA and similar thermoplastics (Jones et al., 2011; Kentzer et al., 2011). As a CBPP project, all the designs produced are released under a Commons-oriented license, the GNU General Public License. It is important to emphasize that because several RepRap's parts are replicable (i.e., the RepRap project strives at best to develop a machine that can make most of the parts for a second machine) and its designs are open, it has been an object of social experimentation, thus, creating numerous enthusiasts and communities interested and supporting various RepRap models. Hence, to gain more insights, apart from studying the designs of RepRap, we participated in the email list of the Athens-based hackerspace and joined online foras of FOSS and open hardware communities, such as the Ubuntunistas and the RepRap community. Through this interaction we got a much better idea on the mechanics and learned, amongst others, about Arthur Sacek's milling machine[4] which was built completely out of Lego. The latter worked firstly as an affirmation that building such a sophisticated machine from Lego is possible, and secondly as a motivation to do something better based on a well-known CBPP 3D printer.

We realized that our next step should be to choose and set up a microcontroller, i.e., a small computer on a single integrated circuit designed to sense the environment and affect its surroundings by controlling motors, sensors and other actuators. We needed a low-cost, open source single-board microcontroller which could be customized to serve our project's purposes. People from the Commons-oriented communities suggested that we use the Arduino, Raspberry Pi or just the Lego NXT intelligent bricks, discussing their pros and cons. Arduino[5] is a microcontroller designed to make the process of using electronics in multidisciplinary projects more accessible, whereas Raspberry Pi[6] is a single-board computer with the goal of promoting the teaching of basic computer science. Both can be built by hand or bought assembled for an affordable price; are based on FOSS; and are open, i.e., everybody can study their hardware reference designs while taking for granted an essential knowledge base.

However, we chose to use Lego mindstorms' NXT intelligent brick which, although less powerful, is included into the kit we had already bought. Searching on the web and posing questions in open hardware communities' fora we found out that the NXT intelligent brick could meet our needs and there was no reason to look for another microcontroller, at least during that stage. It is worth mentioning that Lego has released the firmware for the NXT intelligent brick as open source; however, the price of a NXT is higher, even though its processing capabilities are weaker, than an Arduino or a Raspberry Pi board[7]. We

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[3] See the RepRap family tree: http://reprap.org/wiki/RepRap_Family_Tree. (Accessed 28 July 2013).

[4] Watch a Youtube video of Arthur Sacek's functional Lego-built milling machine: http://www.youtube.com/watch?v=pX1cO2XhMrg (Accessed 28 July 2013).

[5] See the homepage of the Arduino project: http://www.arduino.cc/ (Accessed 28 July 2013).

[6] See the homepage of the Raspberry Pi project: http://www.raspberrypi.org/ (Accessed 28 July 2013).

[7] For a comparison of their features and limitations see: Dennis A (2013) *Raspberry Pi home automation with Arduino*. Birmingham, UK: Packt Publishing, and http://blog.makezine.com/2013/04/15/arduino-uno-vs-beaglebone-vs-raspberry-pi/ (Accessed 28 July 2013).

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Table 1
Expenses table (valid as for June the 1st 2013, Greece).

Component	Price
Lego Mindstorms NXT v2.0 Retail Kit	300 EUR
Lego Mindstorms Add-on Kit	90 EUR
Arduino Uno (and motors)	80 EUR
Raspberry Pi (and motors)	95 EUR
Lego Racks	15 EUR
Spare Lego Parts	Undefined
Spare Electronic Components	10 EUR
Total (Lego Mindstorms NXT)	415 EUR
Total (Arduino Uno)	195 EUR
Total (Raspberry Pi)	210 EUR

must also highlight that the original Lego firmware was replaced by leJOS, an open source firmware made to combine the power of the Java programming language with robotic applications. Commons-oriented communities provided us with the necessary information to properly flash the firmware on a Linux operating system. The Lego NXT intelligent brick could function for a limited amount of time due to six AA batteries which were primarily used to provide power supply. Thus, the supply system was modified with the six AA batteries being replaced with an AC/DC power adapter. The bill of materials amounted approximately to 415 euro (Table 1). Nevertheless, if another microcontroller was used, it is estimated that the cost would approximately amount to 195–210 euro.

In the meantime, three individuals and a Commons-oriented media lab came in contact with the initiator of the project willing to contribute. It has been typical in CBPP projects to observe large differences in the number of contributions by different authors (Ortega et al., 2008), and this small-scale project is no exception. The new participants would help in creating graphic artwork, audio and other data assets to sharing expert knowledge on 3D printing, G-Code language and promoting this particular project. However, the main initiator would undertake most of the work necessary to fully materialize the project.

Having set up the microcontroller, at that phase we had to deal with the design and the construction of the mainframe. In this task the knowledge Commons as well as the numerous Commons-oriented communities that have been built around the RepRap project served as an invaluable source of information and learning-by-doing. Almost anyone can make a RepRap 3D printer using steel parts, steel tubing and other non-coherent parts. Nevertheless, these hard-to-craft components arguably eliminate individuals and groups, who do not have essential crafting skills, from building self-fabricating machines. We assumed that because of Lego's modularity and user-friendliness, constructing such a complicated machine would become an easier task. Further, a Lego-built sophisticated machine can by default "deprint" itself since –and this is a main advantage of a voxel-based manufacturing approach– it consists of numerous bricks (voxels) which can be easily dismantled (and then reassembled accordingly).

The Mendel model, named after the geneticist Georg Mendel, was the basis and the pattern upon which our machine would be built, as it is one of the most well-known RepRap 3D printers. Studying its mechanics, it became clear that the mainframe must provide super stability, making the carriers and carriages capable of moving in a straight line. So, special nettings (Fig. 1, see where the arrows point to) had to be constructed so as to retain the carriers and carriages in proper position and solve inertial problems. It is important to emphasize that the final design of the mainframe was achieved through a

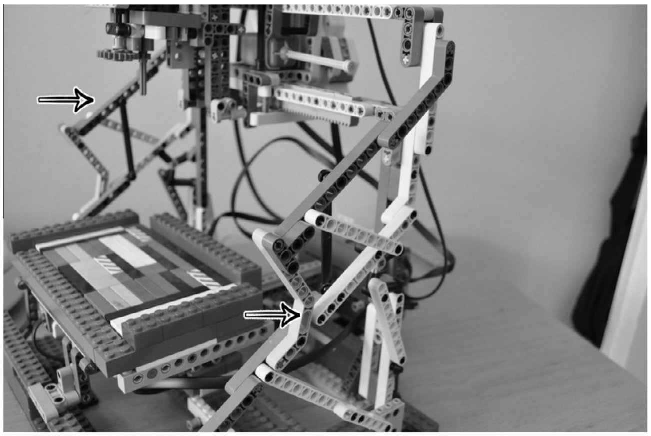

Fig. 1. The final structure of the mainframe (the arrows point to the special nettings).

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Fig. 2. The 3D design of the chuck (left) and the 3D printed one (right).

constant learning-by-doing-community-consulting and so forth process. The overall, final structure of the mainframe has a height of 36 cm, a width of 30 cm and a length of 29 cm (Fig. 1).

Concurrently, we were programming the microcontroller, i.e., the ‘brain’ of our forthcoming machine, according to our needs. The appropriate software was written in Java, using open libraries that enable communication with the NXT. In addition, we analyzed and split proportionally the G-Code files, a language with which humans tell computerized machines what to make and how, in order to be fathomed by the NXT. After that, individual code blocks were written for each one of the numerical commands, i.e., on two or three dimensions. All the software is distributed under the GNU General Public License while our project’s documentation has been released under the Creative Commons license. The source code is also hosted at a Commons-oriented platform, GitHub.

Moreover, due to modularity we had the capability of either putting a milling bit, making it a subtractive manufacturing machine (i.e., a milling machine), or an extruder, thus making it an additive manufacturing machine (i.e., a 3D printer). It would be interesting to provide a short summary of what an extruder and a milling bit do and how they operate. Firstly, extrusion is a process used to create objects of a fixed, cross-sectional profile. A material is pushed or drawn through a die of the desired cross-section. The two main advantages of this process over other manufacturing processes are its ability to create very complex cross-sections and work materials that are brittle, because the material only encounters compressive and shear stresses (Oberg et al., 2000). Commonly extruded materials include metals, polymers, ceramics, concrete and foodstuffs (Oberg et al., 2000). On the other hand, milling is the machining process, widely used in CNC machines, based on the subtraction of material. This means a computer, based on a design file, controls the shaping of the material using rotary cutters to remove accordingly material from a workpiece.

Being unable to find appropriate Lego bricks for a functional, fit-in drill chuck, we thought to take advantage of the 3D printing fabrication capabilities. In particular, we contacted the Commons-oriented media lab, which had expressed interest in supporting our project, and asked to 3D print and then send to us by regular post the drill chuck. We designed and emailed them the 3D model of the drill (in STL format) and after a few days a package with the customized plastic module reached our doorstep (Fig. 2). Therefore, after some adjustments, we had a working RepRap-based, Lego-built milling machine performing our first trial which was the design of a simple cube (Fig. 3). A video demonstration of it was also uploaded to YouTube (2013). It would be interesting to mention that the milling functionality needs totally 17.2 Watts of power: 7.2 Watts for the NXT Brick and its components, i.e. servos and sensors, and 10 Watts for the drill. We could argue that it is energy efficient with very low costs of operation, even on an extended daily basis.

Hence, we had now to deal with the additive manufacturing capability of our machine. While by putting an extruder instead of the milling bit we could render the machine capable to achieve additive manufacturing practices, it caused thermal problems. For example, as mentioned above, the materials used for low-cost 3D printing are mainly thermoplastics, such as PLA or ABS. However, the Lego consist of ABS which has a relatively low melting point and extensive heating, can damage them. In February 2013 we made a presentation for the Athens-based hackerspace where we had the chance to discuss vis-a-vis with the community there several issues about our project. Talking over our effort to add an extruder and the emerging problems, we realized that the latter could be confronted by insulating regularly heated parts, namely the extruder heater and the bed. Hence, we firstly created the ideal 3D model of our extruder, based on RepRap’s and Ultimaker’s (another open hardware 3D printer) extruder, and then tried to build it using Lego bricks. The result was quite promising (Fig. 4) and now we are trying to make some final, crucial adjustments for a fully functional 3D printing-milling machine.

3.3. Discussion of the case

The development of our 3D printing-milling machine begun in January 2012 and at the time of this writing is still under progress, being, as a typical CBPP product, an unfinished artefact permanently open to further social experimentation (Bruns, 2008). Inspired by and built upon a globally accessible knowledge Commons, a non-expert, who had very basic knowledge of mechanics (i.e., no more than of a typical high school student) and basic programming skills (i.e., being able to control the turtle of the LOGO educational programming language), managed with the support of Commons-oriented communities to create such a sophisticated, quasi-functional (for the time being), hybrid voxel-built machine. This case, amongst others, makes evident CBPP’s cost-effectiveness leading to the social reproduction of CBPP projects while promoting learning-by-

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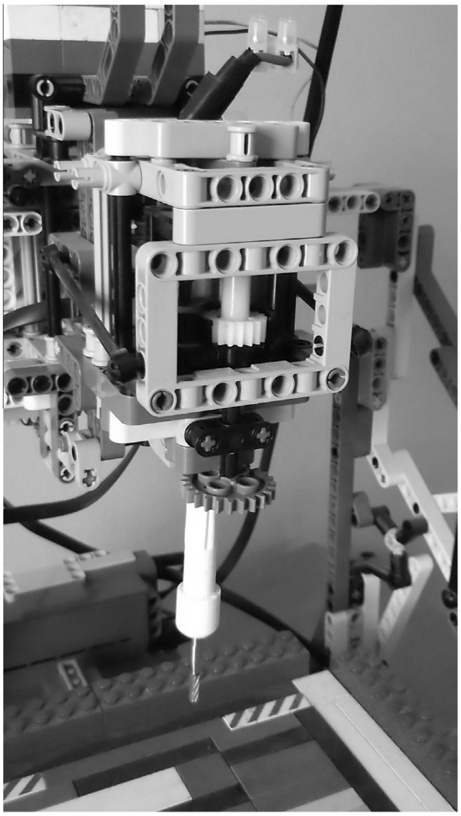

Fig. 3. Testing the working drill.

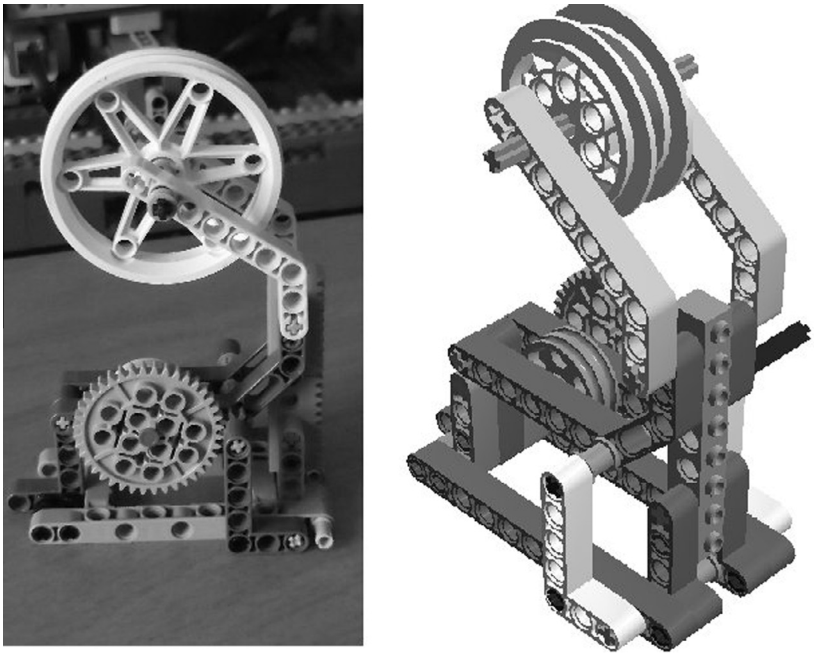

Fig. 4. The 3D design of the extruder (right) and the Lego-built one (left).

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doing, sharing, collaboration and social innovation. To these, hardware components' modularity arguably plays a key role for numerous reasons.

To begin with, the RepRap 3D printer, on which our machine is based, has a high degree of modularity so that many of its components are replicable. This ability, in combination with the open availability of the designs, promotes the social experimentation on the RepRap project, creating several communities interested in and supporting different directions and versions of it. It could be argued that any hardware project which follows a voxel-based approach while distributing freely the designs, can be replicated more easily by more people. In other words, a CBPP product can simultaneously serve as a means for other CBPP projects which can use and build upon various elements or aspects (modules) of the former.

Further, the relation of modularity with hybridism is brought to the fore. Because of the inherent modularity in the voxel (Lego)-based approach to manufacturing, our product can fit either a milling bit or an extruder, transforming into a milling or a 3D printing machine. Grosu, Stauner and Broy (1998:75) postulate that 'modularity is vital for hybrid systems not only because it allows to handle large systems, but also because hybrid systems are naturally decomposed into the system itself and its environment'. This implies, as already mentioned, that the modular, hybrid hardware artefacts are intrinsically capable of 'deprinting' themselves helping in optimizing resources management. Moreover, the multi-functionality, which hybrid systems feature, is cost-effective since one does not have to purchase multiple systems, but has the chance to merge functionalities as well as to customize and modify a machine accordingly.

Also, we have claimed that modularity promotes learning-by-doing, experimentation and, therefore, innovation. Assembling and dismantling our object, till we achieve the desired structure or result, comes with low additional cost in terms of money and environmental burden (the 'throwaway culture' could be mitigated). That is to say, during the process of experimentation and change of our object's structure there was no need to buy extra components: Once fabrication is digitized one can more easily try different morphologies, structures and, thus, functions; as, for instance, we did while developing our fit-in drill chuck.

It would be important to highlight that although our project is not a product of (direct) mass collaboration as Wikipedia or other prominent CBPP are, it is a product of both direct and indirect, asynchronous and real-time collaborative efforts. Actually what CBPP celebrates –and this becomes evident with our case– is the stigmergic collaboration. In its most generic formulation, according to Marsh and Onof (2007:1), 'stigmergy is the phenomenon of indirect communication mediated by modiflcations of the environment'. Therefore, in the context of CBPP, stigmergic collaboration is the 'collective, distributed action in which social negotiation is stigmergically mediated by Internet-based technologies' (Elliott, 2006). The production efforts for developing our machine were often based on various traces (i.e., information in the form of knowledge, designs, discussions etc.) left in a networked environment by others' actions, while our own actions may stimulate the performance of a next action, by the same or different agents.

Further, the advantages of standardization (not only standardizing the interface between components, so that all parts can fit together, but also their design, making their production cheaper) as well as the advantages of customization (various unique objects can be made with certain components) are manifested through the fabrication of our hybrid machine. Its elementary parts (i.e., the simple Lego cubes) can be disassembled and re-used, and combined with less versatile, but more specific building blocks, (such as the constructed drill chuck) enhancing customization. In our case study's modular construction system, everyone is free to combine or even design and produce (with the help of desktop manufacturing capabilities such as 3D printing or laser cutter) parts to develop the machine in similar or different directions. However, these have to be compatible with each other, i.e., they have to follow a basic set of rules. For instance in our project, any new part has to be designed according to Lego tubes' pattern – stubs and holes – so that they can fit-in.

Our case study, a conjunction point of CBPP products and processes with the voxel-based approach to manufacturing (that is, digital fabrication), attempts to designate modularity as a common characteristic as well as a catalyst to the former's transferability into the manufacturing of tangible objects. For instance, in FOSS projects the code is being written by a large amount of contributors who build a part of something larger. Because all peer contributors adhere to a basic set of rules, large amounts of dispersed individuals and communities can engage in meaningful collaborative efforts – often coordinating through asynchronous, stigmergic communication – and contribute parts that are inter-compatible. The same approach can be applied to physical manufacturing if modular productive systems are adopted. In terms of openness, one key disadvantage of the fabrication process of our Lego-built 3D printing-milling machine is the fact that Lego is a 'closed' system. The company controls, for example, the material or the colors of the voxels and nobody else is allowed to produce Lego pieces. If we speak of CBPP transferability to physical manufacturing based upon digital fabrication processes, we have to be careful of the openness and the distribution of the modular parts and be aware of monopolistic situations where all parts are designed and produced by one manufacturer. CBBP, as discussed in previous sections, has already shown the advantages of open production ecologies over the closed ones.

An attempt to transfer CBPP practices and values into the physical production creating open, modular design and building ecologies is the OpenStructures (OS) project. According to its website (OpenStructures, 2013), OS 'explores the possibility of a modular construction model where everyone designs for everyone on the basis of one shared geometrical grid'. It initiates a kind of collaborative construction system to which 'everybody can contribute parts, components and structures'. Projects like our case study or OpenStructures, premised on modularity, can create dynamic instead of static objects/artefacts. Thus, the production value chain is transformed to the point of being entirely unrecognizable in the same style as happens in CBPP (Bruns, 2008). Various users would act incrementally as producers by gradually extending and improving the parts present

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in the design commons. This means that it will not be clear anymore who designed them: 'An object evolves as it is taken in hands by more designers' (Lommée in De Decker, 2013).

4. Conclusions

This essay set out to show, through the case of the RepRap-based, Lego-built 3D printing-milling machine, two points: First, on a theoretical level, that modularity, not only in terms of development process but also of hardware components, can catalyze CBPP's replication for tangible products enabling social experimentation, learning and innovation. Second, that the synergy of a globally accessible knowledge Commons as well as of the CBPP practices with digital fabrication technologies, which are advancing and becoming more and more accessible, can arguably offer the ability to think globally and produce locally. Of course, there are several 3D printers as well as CNC machines on the market; however, through our case study, it became obvious how the synergy of CBPP practices and tools with modular hardware components can offer innovative, novel products, such as a hybrid 3D printing-milling machine. When hardware becomes modular, we saw and discussed how individuals – no matter their age, level of expertise and initial skills – could engage in stigmergically collaborative productive processes of designing, programming and manufacturing. The parts and components of modular objects could be re-used for their own improvement or for the design of other products, enabling collaborative (and thus incremental) innovation within hardware construction. Taking into consideration the trends and trajectories of the current information-based societies, the fact that a non-expert can take advantage of a peer produced knowledge Commons and of very elementary digital fabrication capabilities and become capable of developing such a sophisticated machine, in collaboration with others, can be considered a positive message indeed.

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References

Anderson, C., 2012. Makers: The New Industrial Revolution. Random House, London.

Bauwens, M., 2005. The political economy of peer production. Ctheory Journal. Available at: <http://www.ctheory.net/articles.aspx?id=499> (Accessed 28 July 2013).

Bauwens, M., 2009. Class and capital in peer production. Capital & Class 33 (1), 121–141. http://dx.doi.org/10.1177/030981680909700107.

Benkler, Y., 2006. The Wealth of Networks: How Social Production Transforms Markets and Freedom. Yale University Press, New Haven/London.

Benkler, Y., 2011. The Penguin and the Leviathan. Crown Publishing Group, New York.

Bruns, A., 2008. Blogs, Wikipedia, Second Life, and Beyond: From Production to Produsage. Peter Lang, New York, NY.

Carson, K., 2010. The Homebrew Industrial Revolution: A Low-Overhead Manifesto. BookSurge Publishing, Charleston, SC.

Dafermos, G., 2013. Governance structures of free/open source software development. Next Generation Infrastructures Foundation, Delft.

Dafermos, G., Söderberg, J., 2009. The hacker movement as a continuation of labour struggle. Capital & Class 33 (1), 53–73. http://dx.doi.org/10.1177/030981680909700104.

De Decker, K. How to make everything ourselves: Open modular hardware. *Low-Tech Magazine*. Available at: <http://www.lowtechmagazine.com/2012/12/how-to-make-everything-ourselves-open-modular-hardware.html> (Accessed 28 July 2013).

Elliott, M., 2006. Stigmergic collaboration: the evolution of group work. M/C Journal 9(2). Available at: <http://journal.media-culture.org.au/0605/03-elliott.php> (Accessed 28 July 2013).

Gershenfeld, N., 2007. FAB: The Coming Revolution on Your Desktop: From Personal Computers to Personal Fabrication. Basic Books, Cambridge.

Gershenfeld, N., 2012. How to make almost anything: the digital fabrication revolution. Foreign Affairs 91(6), 42–57. Available at: <http://cba.mit.edu/docs/papers/12.09.FA.pdf> (Accessed 28 July 2013).

Glover, L., 2006. From love-ins to logos: charting the demise of renewable energy as a social movement. In: Byrne, J., Toly, N., Glover, L. (Eds.), Transforming Power: Energy as a Social Project. Transaction Publishers, New Brunswick, NJ.

Grosu, R., Stauner, T., Broy, M., 1998. A modular visual model for hybrid systems, in Ravn A. Rischel H., Formal techniques in real-time and fault-tolerant systems, Springer, Berlin Heidelberg, Berlin. Doi: 10.1007/BFb0055338.

Hazeltine, B., Bull, C., 1998. Appropriate Technology: Tools, Choiaces and Implications. Academic Press, San Diego, CA.

Hiller, J., Lipson, H., 2009. Design and analysis of digital materials for physical 3D voxel printing. Rapid Prototyping Journal 15 (2), 137–149.

Hiller, J., Miller, J., Lipson, H., 2011. Microbricks for 3D reconfigurable modular microsystems. IEEE Journal of Microelectromechanical Systems 20 (5), 1089–1097.

Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C., Bowyer, A., 2011. RepRap – the replicating rapid prototyper. Robotica 1, 177–191. http://dx.doi.org/10.1017/S026357471000069X.

Kentzer, J., Koch, B., Thiim, M., Jones, R.W., Villumsen, E., 2011. An open source hardware-based mechatronics project: the replicating rapid 3-D printer. Mechatronics, 4th International Conference On: 1–8. Doi:10.1109/ICOM.2011.5937174.

Kostakis, V., 2013. At the turning point of the current techno-economic paradigm: Commons-based peer production, desktop manufacturing and the role of civil society in the Perezian framework. Triple-C: Cognition, Communication, Co-operation 11 (1), 173–190.

Kostakis, V., Drechsler, W., in press. Commons-based peer production and artistic expression: Two cases from Greece. Blackwell, New Media & Society.

Kostakis, V., Fountouklis, M., Drechsler, W., 2013. Peer production and desktop manufacturing: The case of the Helix_T wind turbine project. Science, Technology & Human Values 38 (6), 773–800.

Kumar, K., 1995. From Post-Industrial to Post-Modern Society. Blackwell, Oxford, England.

Lipson, H., Kurman, M., 2013. Fabricated: The New World of 3D Printing. John Wiley & Sons, Indianapolis, IN.

MacCormack, A., Rusnak, J., Baldwin ,C.Y., 2007. The impact of component modularity on design evolution: evidence from the software industry. Harvard Business School Technology & Operations Mgt. Unit, Research Paper No. 08-038. Available at: <http://ssrn.com/abstract=1071720> (Accessed 28 July 2013).

Marsh, L., Onof, C., 2007. Stigmergic epistemology, stigmergic cognition. Cognitive Systems. http://dx.doi.org/10.1016/j.cogsys.2007.06.009.

Oberg, E., Jones, F., Horton, H., Ryffel, H., 2000. Machinery's Handbook, 26th ed. Industrial Press, New York.

OpenStructures, 2013. Available at: <http://openstructures.net/> (Accessed 28 July 2013).

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Orsi, C., 2009. Knowledge-based society, peer production and the common good. Capital & Class 33 (1), 31–51. http://dx.doi.org/10.1177/030981680909700103.

Ortega, F., Gonzales-Barahona, J.M., Robles, G., 2008. On the Inequality of Contributions to Wikipedia. In: Proceedings of the 41st Hawaii International Conference on System Sciences (HICSS '08). IEEE Computer Society.

Rifkin, J., 2011. The Third Industrial Revolution: How Lateral Power is Transforming Energy, the Economy, and the World. Palgrave Macmillan, New York.

Schiller, H., 1981. Who Knows: Information in the Age of the Fortune 500. Ablex, Norwood, NJ.

Schiller, H., 1984. Information and the Crisis Economy. Ablex, Norwood, NJ.

Schiller, H., 1996. Information Inequality. Routledge, New York.

Schumacher, E.F., 2011. Small is Beautiful: A Study of Economics as if People Mattered. Vintage, London.

Siefkes, C., 2007. From Exchange to Contributions: Generalizing Peer Production into the Physical World. Edition C. Siefkes, Berlin.

Tapscott, D., Williams, A., 2006. Wikinomics: How Mass Collaboration Changes Everything. Portfolio, New York.

The Economist, 2011. The printed world. The Economist. Available at: <http://www.economist.com/node/18114221> (Accessed 1 June 2013).

The Economist, 2012. A third industrial revolution. The Economist. Available at: <http://www.economist.com/node/21552901> (Accessed 1 June 2013).

Torvalds, L., 1999. The Linux edge. In: C. DiBona, S. Ockman, M. Stone (Eds.), Open Sources: Voices from the Open Source Revolution, (O'Reilly), pp. 101–109.

Troxler, P., 2011. Libraries of the peer production era. In: van Abel, Bars., Evers, Lucas., Klaassen, Roel., Troxler, Peter. (Eds.), Open Design Now: Why Design Cannot Remain Exclusive. BIS Publishers, Amsterdam, pp. 86–97.

Van Abel, B., Lucas, E., Klaassen, R., Troxler, P., 2011. Open Design Now: Why Design Cannot Remain Exclusive. BIS Publishers, Amsterdam.

Weber, S., 2004. The Success of Open Source. Harvard University Press, Cambridge.

Webster, F., 2002a. Theories of the Information Society. Routledge, New York.

Webster, F., 2002b. The information society revisited. In: Lievrouwand, L.A., Livingstone, S. (Eds.), The Handbook of New Media. Sage, London, England.

Winner, L., 1986. The Whale and the Reactor: A Search for Limits in an Age of High Technology. The University of Chicago Press, Chicago, IL.

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