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Making things in Fab Labs: A case study on sustainability and co-creation

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Abstract
Digital fabrication laboratories (such as Fab Labs) are a global initiative of workshops that offer open access to technologies to produce objects from beginning idea to final production. Fab Labs encourage open and free knowledge sharing among 'experts' and the general public. Claims are being made about community-based digital fabrication workshops transforming practices of design, innovation, production and consumption, while describing positive impacts on the environment and social goals. Research that examines such claims is sparse. This paper explores realities of using digital fabrication technologies within a Fab Lab. It draws on a case study that describes practical outcomes of a design workshop in which a multidisciplinary team engaged in issues of sustainable design and processes of co-creation to design and fabricate a prototype. This experience provides insight into the impact of digital fabrication technologies within a sustainable and co-creational design context and critical reflections are presented.

Keywords: Fab Lab, sustainability, co-creation, digital fabrication technologies

1. Introduction

Community-based digital fabrication workshops are diverse labs where people come together to learn about, use and develop digital tools, technologies and science projects. They are often voluntarily-run spaces that can be freely (at least in part) accessed by the public. Since the setup of the first labs, the number of Fab Labs has grown 'virally' (Gershenfeld 2014) and doubled every 18 months for the last ten years and now amounts to about 350 labs globally (Gersehenfeld 2014). These communities create physical and digital infrastructures to work in community-operated physical spaces or share their learning through websites, documents and conferences. The exchange of knowledge and sharing of digital technologies is key to their collaborations. Fab Labs and their networks constitute prominent examples that usually adapt a workshop model pioneered by the Massachusetts Institute of Technology (MIT).

In recent years, these workshops have gained increased media, government and academic attention because their activities and projects have been linked to ideas that consider these workshops to be part of a digital fabrication revolution creating opportunities for sustainable design. Efforts towards open source, creative commons, peer-to-peer networking and collaborative working have been interpreted as being part of a 'Third Industrial Revolution' (Anderson 2012, 40) and a 'revolution in the making' (Ree 2011, 1). Activities in workshops and the development of affordable digital fabrication tools have been said to put into question the sources and systems of innovation, patterns of co-creation and consumption (Birtchnell and Urry 2012, 2013).

Diverse themes are currently linked to community-based digital fabrication workshops such as peer-production commons (Troxler 2013), personal manufacturing (Bohne 2013), democratisation of invention (Blikstein 2013), co-design (Kohtala 2014) and sustainability (Hielscher and Smith 2014; Kohtala and Bosque 2014). Beyond the hype and some preliminary, recent research (Kohtala and Bosque 2014), significant questions remain unanswered about digital fabrication workshops in practice (Troxler 2010). For instance, workshops might just as easily lead to a dispersal of production capacity and an intensification of consumption that undermines ambitions for sustainability. Academic studies that examine the use of digital fabrication technologies for sustainable design within workshops are rare. Furthermore, the potential of co-creation design activities within a Fab Lab setting are equally underexplored. This paper addresses the need for research into the realities of using digital technologies to influence the production process towards sustainable design and co-creation ideas within a Fab Lab setting. In order to reflect upon these realities, the paper draws on an in-depth case study that consists of practical outcomes of a design workshop conducted as part of a summer school at the University Institute of Lisbon (IUL) within the VitruviusFabLab-Instituto Universitário de Lisboa (IUL or University Institute of Lisbon) Digital Fabrication Laboratory (Fab Lab). The goal of the summer school was to make use of digital fabrication technologies within collaborative teams to design and fabricate prototypes, considering issues of sustainability and co-creation. The aim of the paper, therefore, is to reflect upon the design workshop's processes and outcomes in relation to the summer school goals. Although during the summer school participants were asked to embrace the four pillars of sustainability (environmental, economic, social and cultural dimension) (Magee et al. 2013), critical reflections in the conclusion mainly concentrate on issues of environmental sustainability in Fab Labs.

2. Digital fabrication laboratories

Fab Labs are places where an object can be produced, from its first idea to its digitalisation to its final materialisation (Büching 2013, 117). Across the globe workshops are conceptually embedded in a common set of requirements, technologies and processes outlined in the Fab Lab Charter (Troxler 2010), which is 'to empower, to educate, and to create "almost anything"' (Nunez 2010, 24). Technologies that support the capabilities of creation in Fab Labs include a collection of hardware and software resources. Typically, this includes some commercially available special purpose hardware tools, such as laser cutters, computer numerical control (CNC) milling machines and CNC routers, three-dimensional (3D) printers, but also re-purposed hardware tools, such as toaster ovens used as a cheap alternative for surface mounted electronic component soldering, and self-made tools, such as custom-built vacuum moulding machines. In terms of electronic hardware components, there is often a mix of new components ranging from microcontrollers to sensors, buttons, actuators, motors and wires available. The software needed to design, build or control the machinery is usually comprised of a collection of off-the-shelf commercial applications, such as Adobe Illustrator, but also many open-source alternatives to commercial programs and software that accompanies open-source electronic hardware, such as Arduino.

Fab Labs provide open access to technologies and workshops to encourage free knowledge-sharing. They are commonly open for businesses and the general public, where people can pursue commercial and private endeavours (Troxler 2010). Organisational structures and funding sources vary between Fab Labs. Some of the labs were able to create independent entities, whereas others are hosted by schools, universities or innovation centres. Funding often comes from public sources or from the host, attached with the condition that labs start to self-fund themselves after a few years. A survey of Fab Labs has shown that most labs mainly attract ‘well-educated’ and ‘technology-interested’ people, who look for a space in which they can ‘tinker’ with digital technologies (Walter-Herrmann 2013, 42; Carstensen 2013). Although the access to Fab Labs is meant to be open to everyone, not all demographics are currently represented in the labs. This can result from the labs’ ‘geographical location, the opening hours, (sometimes) the fees, their institutional context (whether they are connected to university, connected to a creative milieu or mainly used by business), and culture’ (Carstensen 2013, 56). Moreover, such exclusion issues go even further when putting them out of the Western context. For instance, the socioeconomic state of countries and regions plays a role whether a $100k Fab Lab (standard setup price) can be built and who can access it. Here, issues of gender, educational background and access to technologies can be even more apparent than in some Western contexts.

3. Digital fabrication in sustainable design

Claims are being made about community-based digital fabrication workshops transforming practices of design, innovation, production and consumption, whilst describing positive impacts on the environment and social goals (Olson 2013). Some workshops aim to enable design and innovation for recycling, upcycling, repair, re-manufacturing, to feed user-led prototypes into sustainable local enterprises, and to realise sustainable design projects (Lipson and Kurman 2013). They might facilitate aspects relevant to post-consumption societies through the sharing economy, peer-to-peer society and collaborative consumption. Nevertheless, some research studies have suggested that future developments of digital fabrication can lead to diminished (resource) scale efficiencies and intensify production and consumption through the possibility of continual, customised manufacturing and uncontrolled production. Although certain studies have tried to examine the possible environmental and social impact of digital fabrications technologies (in particular 3D printers, see Kreiger and Pearce 2013; Faludi 2013) and scenario-building (Birtchnell and Urry 2012; 2013), research that assesses those implications is still rare (Olson 2013).

In the few studies that exist, efforts have been put into assessing the environmental impact of digital technologies through comparing the life-cycle assessments of several technologies (e.g. Faludi 2013) or manufactured items, whilst comparing them to conventional production methods (e.g. Kreiger and Pearce 2013). However, analysing the life-cycle assessment of digital fabrication technologies, such as 3D printers, is not an easy undertaking, in particular when trying to predict possible technical, social and cultural developments of the technology. For instance, Olson (2013, 34) has even argued that the 3D-printer ‘ability to revolutionise manufacturing, including environmental and energy benefits, is a long way from being proven’. Lipson and Kurman (2013, 215) argue that:

> 3D printing won’t be an innately green manufacturing technology unless we actively seek to make it one. If we can tap into 3D printing’s unique capabilities and invent greener printing materials, we will reap environmental benefits in the form of shorter supply chains and a new generation of optimised products.

Transport reduction (or a potential increase) and the potential for re-localising manufacturing is an additional topic that is highly disputed in the literature on digital fabrication and its influence on issues of sustainability. For example, Birtchnell and Urry (2012) have wondered whether transportation (in particular, freight) impacts on the environment could be potentially reduced through manufacturing products locally where they are bought and used, rather than halfway around the world. Within their scenario work, digital design files would be exchanged around the world and the product would actually be created locally in a Fab Lab (i.e. local production). In contrast to this scenario, Olson (2013) has argued that when analysing the transportation impacts, it is also important to consider that digital fabrication technologies need feedstock, raw and building materials, to create these objects that might still have to travel around the globe. Furthermore, the need for resources to create feedstock for building materials raises the issue of possible geopolitical implications within these production processes where countries start to compete to gain access to cheap resources. Such implications might question the sustainability and democratisation aspects of these technologies if resources are more easily accessed by wealthier countries and without any limits.

The above outlined debates seem to imply that the environmental impacts of digital fabrication technologies and associated infrastructures and practices will depend on the technical developments of digital fabrication technologies, future infrastructures of manufacturing products, and supply-and-demand side transportation systems. For instance, providing materials, technologies and infrastructures for recycling might not be enough to encourage people to think about the resource implications of the materials used in the workshops. Social, cultural and economic aspects will influence how people will use these technologies, including the materials required and produced outcomes. Such aspects might even be more important to consider (i.e. how digital technologies and their outcomes will be used and taken up in everyday work and home activities) to be able to break the cycle of waste production and uncontrolled production. The use of digital fabrication technologies in homes, shops and workshops determines how printing processes create waste, possibilities and uptake of recycling, and how many products people might own and how long they will keep them. Some work has started to appear that attempts to consider the use of digital fabrication technologies in relation to sustainability issues, for instance, linking principles of a circular economy to the Fab Lab phenomenon (see for example, Charter and Keiller 2014). Opportunities are being examined surrounding the longevity of products through people fixing and customising them within labs and the re-thinking of waste streams, such as through using scrap materials.

Although work on the use of digital fabrication technologies and links to sustainability has started to emerge, many publications on the topic still tend to elevate sustainability benefits of digital fabrication technologies without being based on empirical work. More research is needed. In particular, it is vital to consider how digital fabrication technologies are currently being used in community-based workshops.

4. The citizen designer: shaping a sustainable future together

Fab Lab activities engage people in making things through collaboration in hands-on projects using digital design and fabrication technologies that are increasingly linked to one another digitally, often through networks using social media (Smith, Hielscher, Dickel, Söderberg and Oost 2013). Fab Labs aim to make digital technologies available to anyone who wants to use them, aspiring to create spaces where diverse people with a common interest (experts and amateurs) can meet, share and learn from one another. Fab Labs often provide the opportunity not only for collaboration but also for co-creation, often associated with ideas of peer-to-peer learning and open source working. Sanders and Stappers (2008, 6) define co-creation broadly as ‘any act of collective creativity, i.e. creativity that is shared by two or more people’. However, co-creation is unique in that it allows the people who benefit from a service, product or process to be developed or improved to actively participate in the creation process. The end-user or customer becomes an equal partner in the creation process (Bason

2010; Benson 2013; Sanders and Stappers 2008). According to Williams (2013), co-creation ‘is the difference between people creating a great idea for you and people working with you to make a good idea great’.

Alongside other methods of participatory inquiry (e.g. participatory action research (PAR)), which are rooted in Scandinavian research projects on user participation from the 1970s (Spinuzzi 2005) in which ‘planning and conducting the research process [involved] those people whose life-world and meaningful actions are under study’ (Bergold and Thomas 2012, 192), co-creation has become increasingly popular in the social and public innovation sectors to address complex, global problems under a sustainable perspective (Bason 2010; European Commission 2013; Mahy and Zahedi 2010). According to Sanders and Simon (2009), ‘the social value of co-creation is fuelled by aspirations for longer-term, humanistic, and more sustainable ways of living. It supports the exploration of open-ended questions’. Fab Labs play a significant role as facilitators of co-creation processes because of their focus on citizen learning and sharing. Although the links between co-creation and sustainability currently are unclear and under-researched, Fab Labs may offer the opportunity to make sustainable design ideas an inherent part of the co-creation process in a Fab Lab. Because Fab Labs are largely community-based digital fabrication workshops, which can typically be freely accessed by the public, ideas and initiatives for change can emerge from the bottom-up as opposed to the usual top-down approach. This decentralised approach to idea generation and innovation (Kralewski 2012) can lead to grassroots innovations—thus being more aligned with the needs of the community (Chilvers and Longhurst 2013; Seyfang and Smith 2007).

Fab Labs signal a paradigm shift in creation and production from expert-driven creation to co-creation, which requires all involved to develop empathy, to share and to accept equal partnership in the creation process. In the co-creation process citizens or end-users receive expert status in the creation team (Sanders and Stappers 2008). Operators of digital fabrication tools in Fab Labs become facilitators of the co-creation process and simultaneously part of the co-creation team. Similar to other co-creation community-based projects, for example as described by Winschiers-Theophilius, Bidwell and Blake (2012, 179), leadership roles are fluid in Fab Labs and experts involved are ‘being participated’. Furthermore, Bilkstein (2013) argues that boundaries between disciplines are dissolved and entirely reconfigured in Fab Labs. ‘History and mathematics become closely related, and so do music and robotics, and this richness results in a more diverse and accepting intellectual environment.’ (Bilkstein 2013, 18)

5. Case study—Lisbon river waterfront: using digital fabrication technologies towards sustainable futures

The Sustainable Technologies and Transdisciplinary Futures 2013 (STTF2013) summer school was a joint six-day initiative of VitruviusFabLab-IUL Digital Fabrication Laboratory and the Centre for Research and Studies in Sociology (CIES-IUL), research units from the School of Technology and Architecture and the School of Sociology and Public Policy of ISCTE-IUL. The STTF2013 summer school brought together 38 participants from 17 countries with a wide range of disciplinary backgrounds and digital fabrication experience, citizens (e.g. commuters), researchers and technical support staff. Nine scientific and social researchers/educators from IUL (the organising committee) and a consultant team, consisting of technical support staff and students familiar with operating the VitruviusFabLab-IUL, facilitated and supported the event. The consultant team also advised in the capacity of commuters additionally to citizens, and became co-creators in the process. The work process and outcome of one of the eight multidisciplinary teams (the commuter project team) has informed the discussions in this paper.

5.1 The commuter project team

The commuter project team consisted of four members: (1) an industrial designer and doctoral research candidate with expertise in environmental sustainability, design and emotion (Italy); (2) a designer and research fellow with expertise in grassroots innovations, sustainable consumptions and design (UK); (3) an educator, researcher and designer with experience in urban interventions, interactive spaces and digital technology tools (Denmark); and (4) a design researcher and educator with expertise in design thinking for economic, public and social innovation and multi- and transdisciplinary design processes (Australia).

5.2 The VitruviusFabLab-IUL

The VitruviusFabLab-IUL is equipped with a 3D printer and a CNC router, which is a digital-mechanical tool that can cut blocks of material into shapes (drilling and turning) as designed by computer-aided design (CAD) technology that includes the 3D modelling software Rhino 3D and Grasshopper, which runs within Rhino and is mainly used to build generative algorithms. Access to the Adobe Illustrator 2D drawing software was also provided. The team was given a material kit that included the open-source electronics prototyping platform Arduino and compatible electronic components, such as light-emitting diodes (LED), a photocell, push button switches, rotary potentiometer (similar to a fader switch for a lamp, it enables a wide range of input beyond the simple on/off switch), temperature sensor and a block of cork (a native and sustainable material to Portugal).

5.3 Project briefing

The challenge of the project was to investigate specific groups that utilise the Lisbon waterfront, near the Tejo River. The goal of this project, for this project team, was to work with commuters to encourage and stimulate public sociotechnical discussion about subjects that would be of interest to the commuters and that address the four pillars of sustainability, including environmental, economic, social and cultural dimensions. The commuter project team would design and create a prototype for local use in a public space along the river that would embrace sustainable technologies and incorporate the four pillars of sustainability.

5.4 The citizen group: commuters

Commuting from A to B is often a solitary and rushed activity. Augé (2002, 55) describes it as the ‘collective without the celebration, the solitude without the isolation’. Lisbon commuters frequent Cais do Sodré twice daily on work days to embark on the 15-minute ferry journey across the Tejo River to and from work. To gain deep insight and understanding of the commuters’ journey and mindset throughout the commute, face-to-face interviews were conducted and videotaped at the location Cais do Sodré. Transcriptions of the interviews guided the initial conceptual development and a problem-framing process. Because members of the consultant team undertook the same daily journey as commuters, they became sounding board and co-creators during the conceptual development, and design and testing of the prototype.

Interviews with commuters revealed two mindsets on their journey. On the way to work they try to quickly get to the other side of the river with as few interruptions as possible, thinking about their day ahead. On the way home, the mood changes: waiting for the ferry to arrive appears disruptive and commuters often start to get bored while generally feeling tired. This particular time and mood space—waiting to embark the ferry on the way home from work—

was identified as a likely point of interaction with the device (prototype) to stimulate commuters to generate new sociotechnical debates. It was envisioned that interaction with the prototype is conceptualised and designed as a meeting point that enables dialogue and exchange (Valkanova et al. 2014) rather than acting simply as another technological enhanced distraction.

5.5 **Conceptual development of the device**

From the beginning of the design process, the project team's activities were configured around the notion of sustainability and co-creation. Through the STTF2013 summer schools' introductory session and hands-on sociotechnical workshop, the team was encouraged to reflect and build social, cultural, economic and environmental aspects represented in the four pillars of sustainability into their final prototype. It was pointed out to the project teams that sustainable technologies needed to include these four dimensions (environmental, economic, social and cultural). This project brief helped to guide the conceptual development and prototyping phase and stood as a reminder that the final outcome would need to address some of these debates, which was not always a straightforward process. The summer school classes provided for additional information and reflection about the design case for the team and served to orient the creative process among the contemporary issues in design, science, technology and culture. The project team began to generate ideas for the final design. Through the STTF2013 summer school classes and team discussions, the team was able to filter from previous ideas and generate new directions to consider. The co-design exercise led by Liz Sanders (Sanders and Stappers 2014) provided an empathetic approach toward sketching the commuter journey quickly through drawings and diagrams, which were then presented in plenum. Members of the local consultant team helped to support assumptions and answer questions about the target users and provided feedback in the presentations. While the format was extremely compressed, the needs, emotions, motivations and struggles of the commuters in Lisbon were becoming more visible to the group to guide our exploration, similar in the way that 'sensitising concepts' (Blumer 1954; Bowen 2008) guide the qualitative inquiry by providing suggestions on where to look without defining the target explicitly.

5.6 Project outcome: Public Transits—grow your community, share your point of view, get to know others

Public Transits (Trânsitos Públicos in Portuguese) is an interactive device that allows commuters to reflect on current social, environmental, cultural and economic issues, whilst in the process creating and feeling part of a wider community of commuters. The Trânsitos Públicos device is designed to be a welcome distraction while commuters are waiting for their ferry to arrive. An important cultural icon of Portugal, an abstraction of manjerico (a basil plant), was chosen to invite interactions in a playful manner. A manjerico plant is offered during the month of June, during the Santo Antonio celebrations, to show love and appreciation. It is a popular tradition for people to buy manjerico in a small vase to offer it to their loved ones. Although particularly popular during June, it is a sign of love and care throughout the year. The abstraction of a manjerico—the manjerico paper plant—is incorporated in the Trânsitos Públicos device asking for input about environmental, economic and social issues relevant to the commuters (Figure 1). These questions aim to trigger conversations among commuters.

Figure 1. Trânsitos Públicos devices: (a) natural manjerico plants; (b) interactive manjerico paper plant with Portuguese public transport signage; (c) LED question display and yes/no (sim/não) buttons for input.

The following scenario illustrates the commuter-device interaction (see Figure 2). The commuter recognises the typical symbols of his journey (a boat, a train) and sees the moving manjerico plant. Intrigued, the commuter approaches the device and reads (on an LED display) a topical question (e.g. Do you know that you help the environment by taking public transport?). The commuter can answer by pressing a 'yes' or 'no' button ('sim' and 'não' in Portuguese). Then the device displays the percentage of other commuters who share her/his view. At the same time the manjerico visualises these results by expanding to a relative position to reflect the same percentage. For example, if 75 percent of people answered the same way as the current user, the plant expands and opens approximately 75 percent. This visualisation helps them feel part of the greater Lisbon commuter community. When inactive, the manjerico display playfully wiggles, inviting the user to answer more questions.

Figure 2. Typical interaction flow with the system: (a) user encounters installation, which poses a question; (b) user discusses the question with another commuter; (c) using the 'sim' and 'não' buttons, the user selects an answer; (d) the manjerico changes shape, expanding to show how others answered the same question; and (e) commuters discuss their responses in relation to the responses of others as shown by the system.

6. Sustainability: Using digital fabrication technologies within a Fab Lab

The Trânsitos Públicos device addresses the four pillars of sustainability on an object level and a conceptual level.

6.1 The object level

The Trânsitos Públicos device had to be made out of a single, medium-density, cork agglomerate block (50 x 50 x 10cm). Cork is a unique material found in Portugal. It is significant to Portugal's cultural heritage and industrial past. The main material component was therefore made out of a locally sourced material, linking the design of the device to the idea of developing local production efforts within Fab Labs and reducing transportation emissions through shorter supply chains. Additionally, cork is a renewable material. When harvesting cork, no tree is cut down or dies from the process. As soon as the harvesting process is complete, the cork can grow back and the tree can be reharvested after several years. Overall, using cork as part of the Trânsitos Públicos device allowed the team to incorporate cultural, economic and environmental aspects into the device in anticipation that commuters could relate to the device and are encouraged to engage with it and look after it, potentially prolonging its life.

Similarly, the second main component of the Trânsitos Públicos device, the manjerico paper plant, is an important cultural icon for Portugal. It is closely associated with the festivities of St Anthony and St John (held in June), where it is customary to offer a home-grown plant, including a poem, to a loved one. For the project team, the plant created an appropriate addition to the overall design. Firstly, it is made out of paper and can therefore be easily recycled. Moreover, the paper plant was sourced from a local shop, hence connecting to principles of re-use rather than purely relying on the assembly of new parts. Secondly, the plant's social and cultural connotations aided the conceptual development of the device. The manjerico plant is meant to remind the commuter of celebratory times with their loved ones and the imminent reunion with them on their way back home, creating an additional possible attachment to the device and a willingness to engage with it.

6.2 The conceptual level

The overall design of the Trânsitos Públicos device is meant to intrigue the commuters in particular, its cultural and social connotations incorporated into the design encourage them to engage with it and reflect on wider sustainability issues. The by-line accompanying the Trânsitos Públicos device encapsulates the social aspect of the device: 'Grow your community; share your point of view; get to know the others.' The commuter's interactions with the device and their ability to influence the content displayed on the device are meant to trigger a realisation that they are part of a wider Lisbon commuter community and aid opportunities for social interactions addressing social sustainability issues. The choice of the manjerico is culturally relevant for Lisbon and will attract attention. A semantic connection between the plant and the health of the environment is proposed with the intention to build empathy for the environmental issue (Cheok, et al. 2008).

Topical questions posed by the device to the commuters (through a programmed Arduino) relate to each of the pillars of sustainability. For instance, environmental issues are triggered through questions such as 'Do you know that you help the environment by taking public transport?' Moreover, economic and social debates are encouraged through questions such as 'Do you support the public strikes?' and 'Have you ever spoken to another commuter while waiting?' These and similar questions will be to a large extent user-generated, aiming to raise awareness, create bonds among commuters about topics, trigger interesting thoughts, create controversy and, as a result, stimulate conversations about motivating environmental, economic and social topics amongst commuters. Increasing interest in the physical interaction with the device and engagement in subsequent conversations should be achieved by including commuters in the question generation. Commuters are invited to suggest topics or topical questions to be submitted via a website for display on the device. The website, although not created during the six-day summer school, was conceptualised as an extension of the installation offering a platform as additional place of interaction and information sharing amongst commuters, thus leading to commuters being in control of the 'machine' instead of feeling being the 'controlled' by the device.

6.3 Reflections on the sustainable design context

The material considerations for making the final prototype were mainly guided by the design brief, rather than purely by digital fabrication technologies. During the STTF2013 summer school, there was a pervasive attitude towards re-use. In terms of the electronic components, most were harvested from cast-off computers and home electronics that were destined for the garbage dump but still provide value, including simple switches, cables and mechanical parts. The team was encouraged to adopt this pragmatic approach, which seems to be deeply integrated into the Fab Lab culture. Moreover, each team was given a piece of cork with the introduction that this should be the main component of the prototype and the only piece available to the team. Such strict guidelines encouraged the team to use its piece of cork wisely.

The overall design was constructed within the 3D design software Rhino (in order to cut the piece of cork into a shape on a three-axis CNC router), but the team regularly cut out paper versions to hold against the cork piece to check whether the pieces on the computer version would actually map neatly onto the piece (without leaving minimal amount of off-cuts). Although two of the team members had previous Rhino skills, such careful and complex planning required the expert help from one of the Fab Lab staff members to develop and check the final design. Even with his help, once cutting the cork piece, the team had to realise that the 3D CAD did not quite fit together in its physical form. Instead of being able to re-cut another cork piece, the team had to adapt the design of the current pieces to make the overall prototype work. The team members felt somewhat frustrated about the fact that they could not re-cut the pieces and therefore had to adapt the design by hand. Although cork represented a renewable material, given the possibility, the team would have preferred to cut numerous versions of the pieces until they fit, rather than adapt the design, creating a lot of wasted materials in the process.

In order to create a prototype with digital technologies that represents the four pillars of sustainability, a significant amount of skilful human authorship is required and a brief that outlines in detail several sustainable design aspects, considering that digital fabrication technologies do not make things—people make things.

7. Co-creation: multidisciplinary team working in Fab Labs

The design challenge given by the STTF2013 summer school was intriguing but also extremely complex. The project team did not only have to develop a theoretical idea but also had to create a working prototype in only six days. Knowledge, exchange and communication among the project teams, the consultant team of the VitruviusFabLab-IUL and commuters occurred (with some limitations) throughout the project development process.

7.1 Understanding the commuter: conceptual development

From the beginning, the project team worked well together, realising and acknowledging disciplinary differences but respecting them and allowing each to have the same 'value' within the process. Whilst brainstorming the concept, all project team members contributed equally. This first phase was driven by an empathy-building enquiry, in which interviews conducted with commuters provided the necessary insight into the Lisbon commuter journey, state of mind and commuters' aspirations during the journey. A generative idea developing toolkit provided by Liz Sanders of MakeTools (United States) helped visualising and communicating particular moods and stages of the journey (Figure 3).

Figure 3. Brainstorming activity: creating commuters' mood and journey map.

7.2 Concept vs. digital fabrication technologies

Project team members fell naturally into roles of existing expertise once the decision about the concept and design of the device was reached. These areas were: (1) Arduino microcontroller programming for display, sensors and servo actuator; (2) 3-D modelling/interfacing with CNC router; (3) design/writing/interface with commuter group; and (4) facilitator of team communication/interface with commuter group/resourcing/design/documentation of process. The Fab Lab consultant team acted as technology advisors and operators of the digital fabrication technologies (such as the CNC router), and were part of the commuter group.

Team members communicated regularly with one another during the creation phase, providing feedback on the status of each task. These meetings were important to ensure that the whole team kept the overall design of the device in mind (considering that each member was immersed in his or her own task). This included frequent communication with the consultant team to discuss emerging ideas regarding the technical viability and social and cultural sensibility. However, disciplinary tensions under the deadline pressure emerged. For example, challenges with the electronics (such as displaying diacritical marks on the LED display, important for the social configuration of the design) appeared to take centre stage, pushing conceptual ideas to the background. The input from the commuter group (represented at this stage by the consultant team of the VitruviusFabLab-IUL) became highly important to keep a balance between concept and what was technically possible. Indeed a key idea, the use of the manjerico as a centre part of the device, only emerged through conversations and input from commuters during this hands-on creation phase. Feedback and advice about topical questions to be displayed on the LED screen was also sought from commuters regarding cultural and social appropriateness and when translating questions into Portuguese.

7.3 Reflections on the co-creation process

The co-creation team (consisting of four members on the project team), Lisbon commuters, and the consultant team in their role as operators of the VitruviusFabLab-IUL overall worked well together as evidenced by the production of a prototype of the Trânsitos Públicos device. The co-creation team created a device that was sensitive to the community and was technically challenging to build. This was only possible through engaging with the commuters in the creation process. Particular insights needed to address the specific needs of the Lisbon commuters proposed the invitation to this citizen group to be part of the co-creation process. This has proven particularly successful when developing an understanding of the cultural and social context of the Lisbon commuter group. The commuter voice was heard throughout the design process—firstly through face-to-face interviews that were conducted at Cais de Sodré, and continuing through members of the consultant team being part of this particular social group and being co-creators in the process.

The mix of expert/amateur status of team members regarding the technology created value-adding perspectives but also tensions. Novice users of digital fabrication technologies challenged preconceptions of the more experienced team members. In lacking experience, capabilities and limitations of the digital fabrication technologies were questioned and alternative solutions were explored (e.g. difficulties in programming the Arduino board were overcome, due to novice team members not accepting pre-conclusions from experienced team members). Awareness of and respect for diverse disciplinary backgrounds was evident throughout the co-creation process. The multidisciplinary mix of the project team helped to create interesting technical and conceptual interconnections. Corroborating common findings on the benefits of multidisciplinary collaboration and participatory design methods (e.g. Fleischmann and Daniel 2013; Sanders and Simon 2009), the mix of disciplines was, in the case of the conceptual development and design of the prototype, needed, as was the interaction of the project team with the Fab Lab consultant team and commuters to achieve the project outcome.

Throughout the creation process, members of the consultant team regularly gave advice and hands-on help, for instance, for the use of digital fabrication software. The operation of the CNC router was observed by the project team for some time but was solely in the hands of a Fab Lab expert. It is important to point out that the Fab Lab consultant team tried to avoid taking leadership in decision-making processes during the development of the prototype but had to educate project team members on appropriate and sensible use of digital fabrication technologies. Learning and sharing amongst the team members were certainly achieved on different levels by accepting complementary disciplinary expertise and the social and cultural knowledge of different team members

The co-creation process required from each member a high level of social competence to decide when to retreat partially from a discussion, when to take a lead and/or when to question a disciplinary decision. Navigation issues of equal partnership were a new experience for the four core members of the project team as they all had experience in leading project work and were used to taking ownership of projects. The four team members agreed that the process felt different to the multidisciplinary team work previously experienced. In agreement with all team members, compromises were made on both conceptual and technical sides of the device in order to create a working and meaningful prototype in the brief time provided.

This available time also caused the iteration process of the prototype to be cut short. Usually end-users take on a significant role when testing the outcome in any participatory design process. However, due to time constraints, commuters did not test the device in its final location at Cais de Sodré. Nevertheless, Lisbon commuters will be able to shape the interaction with the device and therefore communication among commuters in the future, as they are invited to submit questions to a web portal, which will then randomly be displayed on the Trânsitos Públicos device.

8. Discussion

8.1 Sustainability and Fab Labs

The case study has shown that explorations into sustainability are not inherent in digital technologies that make up Fab Labs. The case study was clearly framed around sustainability issues (in relation to the material used and conceptual development) and encouraged co-creation at every stage. Such framings were outlined in the design brief that was introduced to the STTF2013 summer school participants on the first day and reiterated throughout the days and, in particular, whenever the organisers felt that the design team prioritised certain ideas over the four pillars of sustainability. The four pillars of sustainability were therefore key in structuring the development of the final design. Moreover, reflections on sustainability issues were encouraged because of several values held by the expert team that run the Fab Lab (such as to re-use materials instead of buying new ones). The design brief, organisers and consultant team in the Fab Lab were therefore incremental in helping to produce a device that was made up of re-used and renewable materials, incorporated social aspects into its design and considered the various production possibilities.

The provision of digital technologies to a wide variety of people within Fab Labs does not seem to be enough to encourage explorations into sustainability issues. Projects conducted within Fab Labs need to be structured around societal and environmental aspirations. As pointed out by Nascimento (2014, 4), the potential social and environmental value of these labs 'may reside in a clear re-thinking about the specific values, norms and relations, such as sustainability, social justice, fairness or responsibility, to be embedded in artefacts, and at the same time, about the alternative technological and social scenarios that may arise'. The beginnings of such potential re-thinking became apparent within the case study. Instead of being purely driven by the technological capabilities of the digital machines, the summer school team was able to balance their design intention with issues of sustainability. For instance, the team debated whether to purchase new materials or re-use existing ones, whilst in addition having strict guidelines on using a locally produced, renewable material (i.e. cork) and receiving only one piece of it. There was a constant focus on sustainability from materials to design concepts that supported the final outcomes and yet opened the topic for critical reflection about how Fab Labs can support sustainability. The case study therefore demonstrates that Fab Labs can potentially be places that encourage sustainable design, where people can produce products locally and think about the various implications on the environment and society of their design.

Nevertheless, such potential seems to be rarely explored within the Fab Lab network when considering Troxler's suggestion (2013; 2010) that 'labs rarely make use of the possibilities the Fab Lab innovation ecosystem offers' (2010, 8), and therefore the global network of labs currently 'struggles to define its form and purpose' (2013, 181). Similarly, Sterling (2014) is cautious about the current lack of consideration of possible consequences that might arise through the increase of digital fabrication in labs. When examining the literature on Fab Labs in greater depth engagements with sustainability issues are very rare (Cohen 2014). More apparent activities within the Fab Lab network are grounded 'in experimenting for the sake of experimenting, or yet making something only for the sake of using for instance the newest tools of additive and subtractive fabrication' (Nascimento 2014, 4). Such issues might easily lead to a dispersal of production capacity and an intensification of consumption that undermines ambitions for sustainability.

Which attitudes and activities will prevail within the Fab Lab network is currently unclear. Nevertheless, if existing transformative social and environmental claims about labs should become a reality, there might be a need to debate more actively the role of digital fabrication technologies in wider change processes. Arguably, although digital fabrication technologies are not neutral (Nascimento 2014), the case study demonstrates that notions of sustainability are not inherent in these technologies either. They might allow affordances towards incorporating the four pillars of sustainability, but such considerations are not foreseeable or predestined. Within the summer school, the design brief, organisers and consultant team guided such notions, rather than were purely driven by the technologies available to the team.

8.2 Co-creation and Fab Labs

Fab Labs can be seen as an expression of the transforming practices of design, innovation and production. They have the potential to support distributed and open production through facilitating co-creation processes. As seen during the STTF2013 summer school, idea generation can occur from the bottom-up, involving the people who will benefit from the product of the creation process. This is a significant shift from the current production process and can lead to bottom-up innovations. It is almost inevitable that the empowerment of the end-user/citizen in co-creational idea generation and production processes in Fab Labs supports the creation of products that are closer aligned with the needs of the community as evidenced by the Trânsitos Públicos device and suggested by Chilvers and Longhurst (2013) and Seyfang and Smith (2007).

On the other hand, it seems obvious in retrospect of the summer school that the use of digital fabrication technologies within Fab Lab requires the expertise and guidance from experienced people to foster the concerns for sustainability and to provide help in acting as a responsible designer when utilising digital fabrication technologies. The use of these technologies requires skills and knowledge that cannot be easily acquired by participants and, therefore, liberation in the use of digital fabrication technology is currently coupled with a dependency on the technical support team within Fab Labs.

This has implications for collaborations between 'experts' and 'amateurs' in co-creation teams within Fab Labs, considering that equal partnerships might not always be guaranteed when working together with digital fabrication technologies that are rather complex to use. Most people lack the necessary skills to handle and design freely with the currently available technologies. Therefore, Fab Labs appear to be to some extent expert-driven (or at least are expert-led) where access to these technologies for anyone might not be as easily put into operation as proclaimed by the labs. As experienced during the STTF2013 summer school, the paradigm shift of moving production away from expert-driven creation is in its early days. However, early experimentations were apparent during the creation of the Trânsitos Públicos device, which can be considered to be expert-led or expert-assisted co-creation.

The case study further highlighted that the digital fabrication technology and the people who are able to operate it can easily take centre stage in the production process, which might endanger the development of sustainable design ideas. The project team experienced that engaging additional experts with various disciplinary backgrounds in a Fab Lab setting and as partner in the co-creation process does not necessarily lead to dissolving or a complete reconfiguration of disciplinary boundaries between the disciplines as suggested by Bilkstein (2013). While there was certainly a shared understanding of clear purpose and goals of the team, and joint (fluid) leadership roles amongst team members, the case study demonstrated that negotiating between technical and sustainability issues on occasion became a challenge. Existing conceptual ideas, which reflected the social and environmental aspects of the design, were sometimes questioned and even considered to be neglected in order to make the technology work. It took some negotiational efforts from two of the design team members to find compromises between what was technologically possible and the conceptual idea behind the device. When using Fab Labs, it is clearly important to be willing to either learn technological skills, and/or to develop an understanding of the digital fabrication processes before being able to make sensible use of such technologies within a sustainable design context.

One factor often overlooked when working with multidisciplinary collaborations within a Fab Lab, and in particular within such unfamiliar cultural context and technological environment, is time. For multidisciplinary processes to work effectively in Fab Labs (and other settings) sufficient time is needed to allow the development and building of mutual understanding, effective communication and knowledge exchange. This appears to be the case regardless of the level of experience of collaborators in multidisciplinary settings, as became evident in the case study. Clearly more time and experience within a Fab Lab might then lead to a blurring or dissolving of disciplinary boundaries as suggested by Bilkstein (2013).

9. Conclusion

This paper started by drawing attention to the increased media, public, government and academic interest towards Fab Labs, because people's activities and projects within these workshops have been linked to ideas of a digital fabrication revolution, including potentials for sustainable design. The current limited literature shows that there are contentious debates relating to linkages of sustainability and Fab Labs. On the one hand, observers predict a dispersal of production capacity and an intensification of consumption that undermines aspirations for sustainability. On the other hand, others have argued that Fab Labs have emerged in many parts of the world offering opportunities for people to learn skills of digital fabrication that help citizens gain what Gershenfeld (2005) called a true liberal arts education. Here, skills of the privileged few are spread among the many and as a result people are liberated, no longer captive to the existing market offerings or helpless due to lack of basic skills of production. People could therefore influence the production process towards sustainable design and co-creation ideas. The paper critically engaged with a case study that described practical outcomes of a design workshop structured around co-creation and sustainability issues, in order to reflect upon the realities of using digital fabrication technologies within Fab Labs.

The analysis of the case study has identified that there seems to be a gap between the claimed transformative possibilities of Fab Labs and realities on the ground, in particular, in the context of sustainable design. Experiences made in the STTF2013 summer school suggest that the development and implementation of sustainable design ideas are currently not automatically ingrained in digital technologies that make up Fab Labs. It is apparent that approaches to sustainability must be driven from within the Fab Labs (as was the case in the described summer school) and the network to re-think current production and consumption process and consider issues of sustainability.

Similarly, Fab Labs are effective in facilitating the interaction between experts and citizens during the creation process. As was experienced in the STTF2013 summer school, knowledge-sharing is inherent to Fab Lab culture. However, equal partnership of co-creators in the production process is not easily achieved or automatically ingrained. Collaboration is a must when the ideas of citizens (often amateurs) and the digital world (operated by experts) merge, as skills to operate and/or program digital technology are currently not easily acquired. This can pose some limitations for a broad use of digital fabrication technologies amongst the wider community. Nevertheless, access to affordable digital fabrication tools and expert knowledge combined in the co-creation process can provide new sources of innovation that derive from citizens.

Equally important is for participants to bring a variety of skills, understandings and willingness to explore not only digital fabrication technologies but also their use in a sustainable design context. Being able to translate social and environmental aspects into sustainable design concepts is as important as to have the technical knowhow when trying to utilise the labs as spaces for social and environmental goals. Acknowledging the importance of outreach work, thinking about how to introduce citizens to digital fabrication technologies, without devaluing the building of conceptual skills, is key to facilitating activities within Fab Labs that are reflective towards sustainability issues and co-creational processes.

Overall, there are ongoing possibilities for co-creational activities in Fab Labs that consider sustainable design issues through utilising digital fabrication technologies. However, more needs to be done to harness the potential of Fab Labs towards sustainable design ideas if current claims should become a reality. An increased debate about these issues within Fab Labs could, for instance, lead to the development of sustainability guidelines and processes that facilitate co-creational processes. Nevertheless, the consideration of environmental sustainability issues is not only up to the individual lab user and is often beyond the control of Fab Labs when acknowledging wider infrastructural, cultural and economic developments. Decisions taken by technology developers, regulators, investors, materials suppliers, energy utilities, waste infrastructures, and others in the wider social world in which Fab Labs interact, are critical in the way they set the parameters for environmental performance downstream in Fab Labs.

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Figure Caption List

Figure 1. Trânsitos Públicos devices: (a) natural manjerico plants; (b) interactive manjerico paper plant with Portuguese public transport signage; (c) LED question display and yes/no (sim/não) buttons for input.

Figure 2. Typical interaction flow with the system: (a) user encounters installation, which poses a question; (b) user discusses the question with another commuter; (c) using the 'sim' and 'não' buttons, the user selects an answer; (d) the manjerico changes shape, expanding to show how others answered the same question; and (e) commuters discuss their responses in relation to the responses of others as shown by the system.

Figure 3. Brainstorming activity: creating commuters' mood and journey map.