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COMMONS-BASED TECHNOLOGY IN THE DIGITAL ERA: THE CASE OF ESTCUBE

Master's Thesis

Technology Governance and Digital Transformation

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Tallinn 2019

I hereby declare that I have compiled the paper independently and all works, important standpoints and data by other authors has been properly referenced and the same paper has not been previously presented for grading.
The document length is 11,047. words from the introduction to the end of conclusion.

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ABSTRACT

With the rise of digital manufacturing, Commons-based peer production (CBPP) practices are moving from distributed production of digital information into the realm of material production. ESTCube, a CubeSat Estonian grassroots initiative, represents an emergent case of Design Global Manufacture Local (DGML), which is a new productive model that merges CBPP with digital manufacturing, proposing a blueprint for CBPP practices in physical manufacturing. Three points support our conclusion: ESTCube represents an in-progress extreme case of Open Source Hardware (OSH) innovation practice; a critical case of CBPP in digital manufacturing, presenting the main features of hackerspaces/makerspaces; moreover, ESTCube's global organization also resembles CBPP ecosystems in the realm of digital manufacturing.

Keywords: CubeSat, Makerspace, Digital Manufacturing, Commons-Based Peer Production (CBPP), Design Global Manufacture Local (DGML), Open Source Hardware (OSH)

LIST OF ACRONYMS

ADCS - Attitude Determination and Control System

CAD - Computer-Aided Design

CAM - Onboard Camera

CBPP - Commons-Based Peer Production

CDHS - Command and Data Handling System

COM - Communications System

COTS - Commercial Off-The-Shelf

CSD - CubeSat Design Specification

DGML - Design Global Manufacture Local

DIY - Do It Yourself

EPS - Electrical Power System

ESA - European Space Agency

ESEO - European Student Earth Orbiter

FOSH - Free and Open-Source Scientific Hardware

GS - Ground Station

ICT - Information and Communication Technologies

IOD - In-Orbit Development

LSF - Libre Space Foundation

MCS - Mission Control System

OSD - Open Source Definition

OSH - Open Source Hardware

OSPD - Open Source Product Development

OSS - Open Source Software

PECS - Plan for European Cooperating States

PL - Payload

SME - Small and Medium Enterprises

STR - Satellite's Structure

VoIP - Voice over Internet Protocols

1. INTRODUCTION

The conception of information as digital commons has been linked from the beginning with the use of information in distributed networks of collaboration and open source initiatives (Benkler 2006). This conception was boosted by a recent shift, directing the investigations from open source software solutions toward prototypical material applications of open hardware (Kostakis et al. 2015). This new mode of production has not been explored in its fabrication and production capabilities until recently, with the development of fabrication labs and makerspaces (Gershenfeld 2007; 2012). The convergence of "digital commons" with local manufacturing, adopting the shape of collaborative distributed networks, could be one of the blueprint organizational best-practices of the Information and Communication Technologies (ICT) paradigm. Novel adoptions of this model should be found in areas of activity closely related to the characteristics of this new production model. Yet such practices have been mostly identified in the primary and secondary sectors, e.g. open source seed-sharing networks and community seed banks or low-cost machines for agriculture (Dafermos and van Eeten 2014; Kostakis and Bauwens 2014).

The objective of this thesis is to contribute to the advancement of the current understanding of a new productive model called Design Global Manufacture Local (DGML). A case study will be presented, in which we aim to explore the possibilities of DGML in an area of great complexity and frugal innovation, that seems to agglutinate some extreme characteristics of Commons-Based Peer-Production (CBPP).

The author aims to contribute to the aforementioned research by identifying and researching a case study where the convergence of digital commons and digital manufacturing, localized in a small space research community, may be key. Thus, certain characteristics of this community could be featured, enabling it to take part in an area of activity where the barriers to entry used to be significantly high.

The unit of analyse is the ESTCube project, which is organized through the Estonian Student Satellite Foundation (ESTCube) and based at the University of Tartu (Estonia). The main objective is to analyze how and to what extent the ESTCube fits into the Design Global Manufacture Local (DGML) productive model (see Kostakis et al. 2015; 2018), and to shed light on the main drivers and barriers that enable or limit the implementation of DGML in this case study. Principal research question: what are the similarities between ESTCube and the principles of the DGML model? Secondary research questions: What are the similarities between Estcube ecosystem and a CBPP ecosystem? What are the similarities of ESTCube and the characteristic values of makerspaces and hackerspaces?

The investigation of the ESTCube case study aims to explore the relevant ecosystem, organization, and outcomes, highlighting evidence that connects the selected case with the theoretical framework. Important parts of the background with its contextual information are retrieved from previously unpublished research of the author in the context of his current graduate studies. Finally, the main conclusions and boundaries of the used methods are discussed.

Plan of the thesis. First, we will go through the literature review, focusing on the new peer-production ecosystem, the implications of the recent developments on digital manufacturing for this production model, its values, good governance characteristics, and the business opportunities arising in the realm of Open Source Hardware (OSH). Second, we will resume the methods used during the research. Third, the ESTCube case study will presented.

2. THEORETICAL FRAMEWORK

The theoretical framework is divided in two parts, each of them focused in one different area of this research. The first part is focused in the concept of Design Global Manufacture Local, that is closely connected to Commons-based Peer Production, and in some of its most relevant underpinning ideas for this case study: the makerspaces as physical facilities, and foundations as emergent organizational best practice. The second part of the theoretical framework is connected with technological tools, and organized around the wider concept of Open Source Hardware, that is key for the future development of Design Global Manufacture Local, while pinpointing one subclass of Open Source Hardware called Free and Open-Source Scientific Hardware that is closely related to the specific technology studied here, the CubeSats. To close this section, the business models related to Open Source Hardware connected to the supposed sustainability of Design Global Manufacture Local.

2.1. Design Global Manufacture Local productive model

In the first part of the theoretical framework the author's aim is to show how DGML model proposes a novel way to organize digital manufacturing, by using makerspaces as grassroot community microfactories and foundations as novel organizational frameworks for CBPP ecosystems that are developing around the emergent 'digital commons'.

2.1.1. Commons-Based Peer Production

The idea of the "commons" pertains to communities which follow specific rules with the aim to fairly manage common resources (Bollier, 2014; Ostrom, 1990). Apart from shared material resources, there are also the emerging digital commons, including designs, software, and knowledge (Roos, Kostakis and Giotitsas 2016). The widespread adoption of ICT empowers people to use, modify and enrich the recorded digital commons under certain protocols. The free encyclopedia Wikipedia and numerous free and open-source software projects thrived due to the low-cost distribution of the digital commons.

Commons-based peer production (CBPP) is a new modality of organizing production based on open collaboration and the sharing of digital resources in a networked environment, which has been enabled by the widespread availability of internet connection (Benkler, 2006) In CBPP, value is added to the system through collaboration and free contribution, rendering monetary factors dispensable in a decentralized, collaborative, and nonproprietary way to coordinate individual tasks without the use of price-based signs or top-to-down managerial command (Bauwens, 2005; Kostakis Fountouklis and Drechsler 2013; Orsi, 2009; Benkler, 2006). While incentives such as profit, competitiveness, hierarchical control and power found in the industrial model are secondary, the learning aspect, community-driven control, community ownership and accountability, openness, collaboration, socialization and experience gained through CBPP endeavors are on the front line (Bauwens, 2005; Benkler, 2006; Kostakis, 2012).

The low thresholds for participation in CBPP initiatives aim at opening the way for contributions. As far as open-source software solutions are concerned, the sharing of goods in a CBPP context does not lead to scarcity but enhances the total value and circulation of the produced solution (Bauwens, 2005; Benkler, 2006). As a result, we are witnessing the emergence of a new ecosystem of peer-produced commons that consists of three institutions: a productive community formed by all contributors producing a sharable resource; a commons-oriented entrepreneurial coalition(s) which aims to create profits or livelihoods using sharable resources; and a for-benefit association that constitutes or supports the organizational infrastructure of productive communities and entrepreneurial coalitions. (Bauwens, Kostakis and Pazaitis 2018)

2.1.2. Design Global Manufacture Local

When it comes to the physical world, the CBPP surfaces in the form of a model that targets sustainability and inclusive production as its goals and it is called Design Global Manufacture Local (DGML). An initial assumption of this model is that through social practice, networked-based collaborative initiatives utilize common intangible and tangible resources to create value (Kostakis et al. 2015). The intangible resources are shared via the internet in the form of the 'digital commons', while the appropriate physical environment and equipment needed for the realization of technological solutions can be commonly used in local makerspaces; thus, "what is non-rivalrous becomes global (i.e. global commons of knowledge, design, software), and what is rivalrous (i.e. hardware) is local" (Kostakis et al. 2018). This convergence of the digital commons with local fabrication technologies available in globally distributed makerspaces facilitates the computerization of the manufacturing process, enabling the democratization of the so-called 'digital manufacturing'. (Gershenfeld 2007)

Meanwhile, the customization and the adaptation potential of the produced solutions in different places is facilitated by the modular structure of the outputs, consisting of a significant advantage associated with the utilization of the DGML model. According to Dafermos and Söderberg (2009) and Kostakis et al. (2015), "modularity is a form of task decomposition". The embedded modularity of the DGML solutions enables different groups to work simultaneously and independently on separate aspects of a project, including the design and the assembly of different parts of the DGML solution. Modularity enhances the capability of asynchronous horizontal collaboration both in a global and local level and constitutes one of the basic characteristics of commons-based peer produced artifacts, and the core principle of DGML distributed networks of production. Modularity is key for DGML, as the digitalized modules can be copied and transmitted at near zero marginal cost (Rifkin 2014) to any connected node of the network, enabling the open replicability of tangible products that facilitate learning and experimentation. (Kostakis and Bauwens 2014)

For modularity to be successfully implemented in distributed networks of production, it is key that the costs of integrating the modules remain low (Benkler and Nissenbaum 2016). Otherwise, the modularized production would not be feasible. The big advantages of task decomposition for distributed production are only applicable if there is a pre-existing and evolving structure designed to integrate the modules. In other hand, DGML is a very recent approach and lacks empirical evidence to sustain its claims on sustainability and best practice model for commons-based approaches to digital manufacturing in the wider context of Industry 4.0.

2.1.3. Makerspaces

Makerspaces emerged as the self-governing physical places where individuals have open access to shared infrastructures and means of production. **(**Anderson, 2012; Troxler, 2011) These spaces may go by various names such as fablabs, hackerspaces, microfactories, techshops, media labs and others, expressing the diversity of the movement. (Moilanen 2012; Gandini, 2015) In such places, people can co-create their own technological solutions by utilizing open-source software and open-source hardware tools, as well as engaging in productive processes which may foster and promote innovation. (Reinert, 2011) According to relevant literature (Saunders and Kingsley, 2016; Moilanen, 2012), socializing and learning are the main reasons why people visit a makerspace. By utilizing local fabrication technologies and forming hybrid community-driven governance models, people in makerspaces engage in activities which offer informal learning practices, mainly focused on manufacturing processes. (Blikstein, 2013)

Some of the main characteristics to collaboratively produce 'solutions' in makerspaces have been identified as openness, community accountability, intrinsic positive motivation, inventiveness with a strong emphasis on technology, sharing tools, ideas, and distribution of tasks. (Kostakis, Niaros and Giotitsas 2014; Moilanen 2012) Makerspaces may be seen as the manifestation of commons-based peer production in the physical realm, and the rising number of makerspaces around the globe manifests the growing trend of this movement. (Niaros, Kostakis and Drechsler 2017) Resembling the rise of the internet, which has enabled low-cost information exchange leading to the democratization of information production, makerspaces enhance the democratization of the production since they provide access to desktop fabrication technologies. (Kostakis and Bauwens 2014; Kostakis, Roos and Bauwens 2016) Moreover, “transferring product development and production activities from industrial practices to the public (...) crystallize in the figure of the so-called ‘maker’”. (Mies, Bonvoisin, and Jochem 2018)

Considering the possibilities for a makerspace to turn into an incubator for entrepreneurship or start-up, the bottom-up innovation potential of makerspaces be highlighted; numerous solutions have been developed in makerspaces to cover the needs of their communities. (Niaros, Kostakis and Drechsler 2017) For instance, the MakerBot 3D printer emerged through two makerspaces which transitioned into a start-up. (Pettis, 2011) Despite some common features, each makerspace with its community is unique (Mikkonen, Vadén and Vainio 2007), especially regarding to the organizational structure. Thus, each case should be thoroughly researched so as to obtain a deeper understanding of the diverse organizational structures found in makerspaces. (Niaros, Kostakis and Drechsler 2017)

2.1.4. Foundations

Foundations belong to a diffuse area of the organizational spectrum. The ambiguity of the status of the foundations arises from its own basic features, that are actually not defining what a foundation is, but what a foundation is not: a non-governmental and not for profit organization. Besides that, its legal requirements present great variations between countries. (Srivastava and Oh 2010) The main contributors to this field of research are either focused on philanthropic private foundations or community foundations, of which both can act locally and globally. (Arnove 1980; Hammack 1989; Carman 2001; Scott et al. 2003; Morgan 2007; Marten and Witte 2008; Nickel and Eikenberry 2010) Foundations would often complement governments as a strange fit in our democratic societies, being mostly out of the scrutiny of public debate while “their full potential remains unmet.” (Stone 2010; Anheier and Leat 2006; 2013) Foundations are also seen as providing sources of innovation and redistribution, challenging the roles of the state and the market as only agents of development, adopting a long-term perspective that is out of reach for democratic governments "driven by electoral timetables and political expediency". (Anheier and Leat 2013)

But exceptional developments are taking place in the area of Open Source Initiatives: Zimmermann (2014) foresees the foundation as a business model platform for open source hardware developers, that would be based on the membership of both individuals and organizations interesting in administering manufacturing collectively, and achieving shared benefits. Besides its business-like functionalities, foundations may also generate standards, create or manage infrastructures or receive grants for funding community initiatives. (Zimmermann 2014)

Foundations are also becoming important players in CBPP ecosystems adopting the role of for-benefit associations, and enabling the autonomy of sharing and collaborative practices. Managing conflicts with stakeholders, fundraising and enhancing the general capacity of the ecosystem through education are some of the functions that such organizations should perform in a CBPP ecosystem, also including the maintenance of the cooperative network that can act recognizing and providing solutions to problems and difficulties of the community. (Bauwens, Kostakis and Pazaitis 2018) Foundations like WikiMedia Foundation or Linux Foundation are examples of for-benefit associations managing CBPP digital ecosystems.

2.2. Open Source Hardware technological framework

Open Source Hardware and its related business models have an important role in the future of DGML. However, the actual circumstances that enable a technological material tool to be opened are constricted by the conditions on the markets, the costs of its recording and documentation, and other circumstances that prevents a digitally manufactured product to be openly shared 'down' into its 'source'. The digital commons are also at the core of Open Source Hardware (OSH), Free and Open-Source Scientific Hardware (FOSH) and CubeSats, and access to open digital documentation of OSH enables the possibility to locally manufacture artefacts. Even if some parts of the design are locally produced or modified, and not added to the global open repositories, it is nevertheless the DGML logic applied to digital manufacturing what opens up the possibility of CBPP ecosystems to emerge locally in makerspace-based communities, designing and manufacturing physical tools by following cost-effective peer-production strategies.

In the second part of the theoretical framework of the thesis, the author aims to showcast the features related to the 'hardwired' part of digital manufacturing and its novel application through Design Global Manufacture Local, both in connection to the case study (CubeSats) and the business models that would allow for-profit and livelihood strategies in CBPP ecosystems, by using open sourced digital manufacturing.

2.2.1. Open Source Hardware

Open Source Software (OSS) is software that has open access to its source code and that it is released under a license that allows its modification and redistribution conforming to the Open Source Definition (OSD). (Feller and Fitzgerald 2000; von Hippel 2001; Krishnamurthy 2005; Open Source Initiative 2007) The characteristics of Open Source Hardware (OSH) have been defined, in its beginning, by its relatedness to OSS features. The main difference between OSS and OSH is that while the basic action for opening the source code of software is as simple as opening and sharing the code that constitutes the software, in the case of OSH such code is nowhere to be found, and in order to create OSH the product itself has to be documented to some degree of detail an exhaustivity. (Bonvoisin et al. 2017; Moritz et al. 2016; OSHWA 2013; Thompson 2011) The development and manufacturing of physical objects also requires different and unrelated uses of tools, motor skills and a material infrastructure that is unrelated to the near only-digital interfaces used to build software. (Raasch and Herstatt 2011) However, OSH is a very novel initiative that lacks thoroughly development, showcasing only a handful of successful stories like RepRap 3D printers and Open Source Ecology agricultural machinery, and it is hard to foresee the upcoming developments during the theoretical 'mature phase' of OSH practices.

Bonvoisin et al. (2017) argue that there are different levels of openness in OSH through its product development. There would be a continuum affecting the average openness of products, starting from the early conceptualization and prototyping, when openness is significantly low, passing through the production phases where higher levels of openness can be found, towards the final and full defined product that coincide with the well documented open source product. However, “the large majority of products show diverse profiles of partial openness without clearly identifiable patterns” (ibid.)*,* something that can be attributed to the early stage of OSH product adoption. A similar pattern is identified regarding the typology of the OSH product: from standardized electronic hardware where most components are purchased off-the-shelf, passing across the more open and not so standardized mechanical hardware, reaching the highest degrees of openness in mechatronic products. (ibid.)

In the case of highly complex OSH products “combining different technologies, made of several parts, designed to satisfy demanding needs” (Mies, Bonvoisin, and Jochem 2019), the collaborative design and practical implementation of collective production from several different contributors acting in parallel rises the integration and coordination costs. (Mies, Bonvoisin, and Jochem 2019; Bonvoisin et al. 2017) In that context, an organizational model that promotes distributed manufacturing in OSH communities, called Open Source Product Development Process (OSPD), aims to effectively tackle such “needs-based problem solving within self-organized processes that span all design phases from conception to manufacturing. OSPD processes (...) require the use of groupware as well as social media to support data management and communication, which are in turn required for effective collaboration, continuity of work, and acquisition of new members.*”* (Mies, Bonvoisin, and Jochem 2019) OSPD aims to provide a comprehensive organizational blueprint for collaborative practices manufacturing complex OSH products.

2.2.2. Free and Open-Source Scientific Hardware

Open Source Hardware is gaining significant traction in the scientific community. (Fisher and Gould, 2012; Pearce 2014) According to Pearce (2017), “there is substantial evidence that the Open Hardware model creates more flexible and adequate scientific equipment at far less expense than has been developed using proprietary models”. OSH has several advantages for scientists**.** First, it lowers significantly the costs of manufacturing the scientific equipment, up to 90-99% of what a scientific hardware provider charges for the equipment. (Pearce 2017; Oberloier and Pearce 2017) Second, OSH provides flexibility to customize and rapid prototype the research tools, which lead to better experiments and faster evolution of science, specially in cutting-edge research where customized never-seen-before equipment is required. (Pearce 2014; 2017) Third, OSH provides increased control over the scientists' labs as they can create, fix, improve or redesign their own scientific open source products, decreasing their dependency on the suppliers of scientific equipment. (Bruns, 2001; Kogut and Metiu, 2001; Pearce 2017)

However, Oberloier and Pearce (2017) detect a lack of standards in the field that hampers the design and manufacturing of FOSH. In order to have an efficient FOSH product, some general design principles can be used, including minimizing the amount of material used and the "number and type of parts and the complexity of the tool" (ibid.), the use of parametric designs, and to get Commercial off-the-shelf (COTS) components whenever it is cheaper and easier to buy them than to build them on the lab, like in the case of screws or printed circuit boards.

CubeSats, being conceptualized as FOSH-like technology from the start, can be seen as scientific tools that space researchers often fabricate themselves. The main difference with other experimental scientific research tools is that, once a CubeSat is finished and launched into orbit, it is never to be seen again on Earth, while the scientists that designed and manufactured the nano-satellite should control and evaluate the experiment from the ground.

2.2.3. CubeSats

A CubeSat is a ten centimeter cube [1U] nano-satellite with a mass of approximately one kilogram, as it is defined in the CubeSat Design Specification (CSD) that set the open source architecture standards for CubeSats as a joint venture between California Polytechnic State University (CalPoly) and Stanford University's Space Systems Development Laboratory since the year 1999. (Swartwout 2013; Hevner et al. 2011; Mehrparvar et al. 2014; Toorian Diaz and Lee 2008, Ampatzoglou et al. 2014) The documentation to build up a CubeSat is freely accessible online, as the CubeSat program aims to provide inexpensive access to space for small payloads (Mehrparvar et al. 2014; Toorian et al. 2005) mediated by collaborating networks of students, amateurs, practitioners, small and medium size business, and with low construction and launching costs and a reduced development time for space experiment platforms, (Straub 2012; Shiroma et al. 2011; Woellert et al. 2011; Heidt et al. 2000) contributing to open the access to space research for small and developing nations. (Carrara et al. 2017; Straub 2012; Woellert et al. 2011; Toorian Diaz and Lee 2008)

According to Koenig (2004) and Zimmermann (2014), an open source initiative has better chances to become a platform and establish an standard in its industry, although a dual licensing represents a better starting point towards fully open sourcing hardware (ibid.), like in the case of complex scientific tools as CubeSats that are often developed by inexperienced amateur teams. There is no consensus on the current state of space research in the area of CubeSats; Selva and Krejci (2012) argue that in few years CubeSats should have outgrown its initial educational purposes to become “a standard platform for technology demonstration and scientific instrumentation”, while for Wollellert et al. (2011) CubeSats are still in its early stages of development.

Regarding existing academic literature documenting the use of OSH in CubeSats, Kief et al. (2011) describe a Space Plug-and-play Architecture (SPA) concept of rapid satellite development built completely from commercial-off-the-shelf (COTS) parts over an open-source bus architecture; Scholtz and Juang (2015) apply a theoretical framework for the OSH application to CubeSats, describing “an increasing number of CubeSat missions that claim to be open source” (ibid.) while they are merely integrating open source modules into their CubeSat design, although they find a prototypical case of open-source CubeSat in LibreCube’s design initiative that “provides information on the LibreCube framework, recommended and applicable standards, naming conventions, and other resources” (ibid.); Ampatzoglou et al. 2014 document the “design, structural analysis, and qualification by analysis and experimental validation” (ibid.) of the Greek open-source CubeSat UPSat, developed by University of Patras and Libre Space Foundation (LSF) in what seems to be, as far as the knowledge of the author goes, the only launched open-source CubeSat that have been documented by academic publications.

An important aspect that have helped CubeSats to become so popular is ridesharing. Rideshares are shared ‘piggyback’ rides as secondary loads in standardized slots in space launchers. In the same fashion that so-called 'sharing economy' startup companies have developed platforms to share car rides, rideshares allow to reduce launching costs by sharing the costs with other CubeSats or complementing primary payloads that are not using all the payload space available in a rocket (Swartwout 2011), open up affordable options to launch low-budget educational CubeSats.

2.2.4. Business Models

Open Source Software business models have been explored and documented during at least the last fifteen years, showcasing the advantages and opportunities that companies can obtain by opening the access of their products to the players in their environment. (Koenig 2004; Krishnamurthy 2005; West and Gallagher 2006; Chesbrough and Appleyard 2007) However, the business models that are relevant to this thesis are the ones connected with CBPP ecosystems: business models for for-benefit associations and for commons-oriented entrepreneurial coalition(s). The latter will be explored in the context of OSH, while the former can be applied to any for-benefit association in a CBPP ecosystem, as foundations do not deal directly with manufacturing.

For-benefit associations are supported by a productive community, not by philanthropists, governments or corporations, usually taking the form of foundations, non-profit organizations or open cooperatives aiming to support the work and practices of a community whose work is dependant on the digital commons. **(**Bauwens, Kostakis, Pazaitis 2018; Benkler 2016; Pazaitis, Kostakis and Bauwens 2017) They can get funded by producing and selling products; membership fees; on-request production through customization and adaptation; supporting services (installing, operating, maintaining, upgrading and/or repairing their products); education and training (workshops, certificates, consulting, events); its own channels (advertisement, product-partnership); funding and crowdfunding; donations (of money, devices or equipment), grants, sponsoring and public research. (Zimmermann 2014; Moilanen 2012) One of the most paradigmatic cases of OSH communities, Open Source Ecology, is reported having their major source of income coming from foundations (52%) and donations (19%), while the revenues from workshops and lectures (24%) are increasing. (Moritz et al. 2016)

Three of the above-mentioned streams of revenue are relevant for this thesis: product partnerships; crowdfunding; sponsoring, grants, donations and public research. Product Partnerships allow for-benefit associations to build hardware using supplies from certain companies through discounts and cross-advertise products; crowdfunding campaigns to help finance the development of working prototypes, while for gaining attention and growing a community of supporters; sponsoring, grants, donations, public research following the claim of an existing public interest behind the product developed, usually channeled through jobs in public research and academic institutions that can support part of the community developing open source hardware. (Zimmermann 2014)

Commons-oriented entrepreneurial coalition(s) use the digital commons connected to a productive community to generate income. It includes do-it-yourself (DIY) business models (Bonvoisin, Galla and Prendeville 2017); business models for makerspaces (Menichinelli 2011); Open Source Product Development Process (Mies, Bonvoisin, and Jochem 2018); Open Source Hardware and Open Design Business Model Matrix (Zimmermann 2014); and also business models to serve scientists (Pearce 2017). According to Zimmermann (2014), OSH business work the same way as any other hardware business, with its main focus on producing and selling goods with a profit. But what are the peculiarities of OSH business models resembling the commons-oriented entrepreneurial coalition(s)? OSH ecosystems can act as incubators for startups, as we have seen in the case of makerspaces, providing companies with multiple advantages regarding technology, people, and process development. (Aksulu and Wade 2010; Mies, Bonvoisin, and Jochem 2018)

OSH communities are very related to CBPP communities, focused mostly on product design and development through digital commons which “creates a downstream potential for commercial activities of OSH-related businesses” (Mies, Bonvoisin, and Jochem 2018) featuring hardware products, assembly kits, components and complementary parts. In such communities, company employees can expand their network of contacts and find opportunities for recruiting talented people, while forming innovation platforms with “multiple product spin-offs”. (ibid.)

In relation to FOSH, there are three different types of business models to serve scientists. The first one consist of the 'makers', that are kit suppliers, specialty component suppliers, and provide calibration and validation services. The second type are 'Open Hardware Buyers' that base their business model on selling OSH and OSH services to scientists. The last type are the 'outsourcers' that provide online services based on OSH, which consist mostly on performing experiments for scientists. (Pearce 2017)

2.3. Integration of both perspectives

The author argues that the organizational principles derived from the logic embedded into distributed informational networks and locally affordable fabrication technologies, have the potential to set the standards for an alternative best-frontier to practice political ecology in the current ICT techno-economic paradigm. To investigate such social practices of CBPP that are evolving on the margins of the dominant productive paradigm, we will examine the DGML model in the area of space research by focusing on the ESTCube project, and its structural resemblance to a CBPP ecosystem. The high note is provided by the fact that CBPP ecosystems in the area of digital manufacturing have been vaguely studied, often in low-tech fields as agriculture machinery. Furthermore, CubeSats are highly complex mechatronic artifacts, better suited for OSH development practices and, as a result, the case study at hand may provide some evidence to contribute towards the exploration of DGML.

3. METHOD

The selected method is a case study. The author finds a meaningful connection to this research topic in the notion that a case study is utilized to shed light on an emerging phenomenon “within its real-life context”, considering the vague boundaries between this phenomenon and its context (Yin, 2003, p.13). Moreover, an instrumental case study was selected since the thesis aims to “provide insight into a particular issue, redraw generalizations, or build theory” (Grandy 2010, p.474). The focus of the case study is connected with an existing set of theories. The outcome of the research aspires to expand our understanding of the state of the art of the related theories, opening new paths for future exploration. Although the selected method is not well suited for drawing generalizations, the results may be serviceable for the expansion and enrichment of ongoing contemporary phenomena (Yin 2003; Grandy 2010). Besides Yin’s instrumental case study approach, the concepts of extreme and critical case studies seem to be also relevant here, as “extreme cases that can be well-suited for getting a point across in an especially dramatic way (...) and a critical case can be defined as having strategic importance in relation to the general problem.” (Flyvbjerg 2006)

The research methods used in the thesis include observation, interview, document analysis, visual data, etc. Online materials from hobbyists and amateur/pro-space enthusiasts, which include big amounts of data on nano-satellites and CubeSats were utilized. The following data collection and analysis tools have been employed in this research: literature review and desk research; structured and semi-structured interviews; in-field ethnographic research

Literature review and desk research was used in particular to investigate appropriate methods, to analyze the main features of the DGML principles and approaches, including CBPP, digital manufacturing, makerspaces and literature for foundations, as well as OSH and its related business models, and finally to review the state of the art of CubeSats and the ESTCube project. Web sources, academic and grey literature, visual and audiovisual data, and other materials were used to collect information on the aforementioned topics. There are many publications about ESTCube and from ESTCube, in generalistic media, specialized online portals, academic publications, blogs, websites reporting events, interviews, and more.

Structured and semi-structured interviews were carried out with different stakeholders in order to gather additional information and perspectives on the ESTCube project and the DGML tools, from December 2018 to April 2019. Six Face-to-face interviews, two voice over internet protocols (VoIP) interviews and several and email exchanges with members of the Estonian Student Satellite Foundation, along with three group informal interview settings were used during the gathering of the data. The main aim of the interviews was to understand the organizational model and relevant features of the ESTCube, as well as the basic elements of the "open" approach implemented through the DGML model. In-field ethnographic research; observation-participation during one international CubeSat conference and one regular weekly workday in one of the two labs that Estcube uses including visits to the Finnish Satellite Workshop 2019 at Aalto University and participating in a co-working day at ESTCube room lab at Physicum (University of Tartu)

The information obtained from the interviews of the Estonian Student Satellite Foundation board members are used in this thesis as a main guidance to make sense of a very broad and diffuse organization through the changes it has passed through during the last eleven years, a transformation that is usually shaped by concrete decisions depending on technical issues.
In the context of DGML, the author benefits from four years of personal contact with some of the most prominent academics on the field.

4. ESTCUBE

4.1. Background information

> *[TV interviewer] Space technology costs millions. Only wealthy countries can afford it.*
> *[M. Noorma] We have a group of immensely talented young students. They are able to do without money the same job that highly paid engineers are doing in the US.*
> *[TV interviewer] So it is a homebrew DIY [do it yourself] project?*
> *[M. Noorma] No, we are using cutting edge technology to build this satellite.*[1]
> (Ligema dir. 2015, min. 12:46)

Is it really possible that a group of students can do the same job, in a volunteer work basis, as experienced well-paid engineers from well-established and conspicuous funded national space agencies? Project Lightsail was the most successful crowdfunding CubeSat campaign up until 2015, raising more than 1,2 million dollars for the purpose of creating a CubeSat that would use solar sail propulsion. (The Planetary Society 2018; Kalnina et al. 2018). Two years later, in 2017, ESTCube-2 started a crowdfunding campaign in Estonia, targeting and raising 30,000 euro for the purpose of creating a CubeSat that would use solar sail propulsion. (Kalnina et al. 2018) The main difference between these initiatives was that LightSail has at its disposal NASA space lab facilities and the support of space research veterans, while ESTCube was using the facilities of a university located in a small country that does not even have a national space agency, and by using the support of a local community of amateur space enthusiasts, students, practitioners and local SMEs. This thesis aims to show how by using a CBPP approach, the same project (e-sailing testing CubeSat) can be developed while

[1] Official English language subtitles on the documentary.

costing forty times less than what the dominant production approach in space research currently costs.

ESTCube defines itself as *"a combination of various initiatives — education, science, technology, as well as student and volunteer organizations"* — that can be briefly described as a community. (Kalnina et al. 2018) It is a Estonian space research grassroot movement mostly supported by Tartu University and Tartu Observatory, that has teamed up with the Finnish Meteorological Institute to perform a three-stage satellite series of e-sailing in-orbit demonstration (IOD) oriented towards educational purposes and space engineers community building. The three stage satellite series is forecasted to occur through the development launching and testing of a three CubeSat series consisting on ESTCube-1, that has been launched in 2013, ESTCube-2, that is currently under development, and ESTCube-3 that would perform the last e-sailing test. After that, if the initiative has succeeded, the research and prototyping phase would be over, and the production phase of mature technology would start; a technology aiming to interplanetary travel, nonetheless.

ESTCube-1 was a collaborative effort with many international partners that started without prior in-house experience, it took five years of development and contributions from around 200 students from 10 countries whose work materialized in over 30 Bachelor thesis and over 20 Master thesis were defended, with 14 scientific articles published, 50 presentations and 4 spin-off companies created (Slavinskis et al. 2015; Lätt et al. 2014), "building the country's first satellite, which made Estonia a space nation, earned ESTCube-1 a place in history and recognition in society". (Kalnina et al. 2018)

ESTCube-2 in-orbit demonstration platform aim is also to test the electric solar wind sail, but this time the orbit would take place outside of the influence of Earth's magnetic field. A continuation from the experience of ESTCube-1, other objective of ESTCube-2 is to "develop a small and competent satellite bus solution". (Ehrpais 2016) ESTCube-2 is designed to test technologies that would be used during ESTCube-3 test of the electric sail in the solar wind environment, for what the satellite should be launched in lunar orbit. (Kalnina et al. 2018)

We can identify the following ESTCube actors as part of a CBPP ecosystem. The productive community is ‘ESTCube’, composed by all its members (students, amateurs, enthusiasts and practitioners) and it is going to be studied on ‘Values’ section. The for-benefit association is the Estonian Student Satellite Foundation, that is going to be resumed as part of the ‘Governance’ section. The entrepreneurial coalition(s) consist of ESTCube-2 as FOSH project, ESTCube spin-offs and startups, and one OSH entrepreneur, coming in the final section of the discussion, ‘Business models’.

4.2. Values

> *"Space pioneers are joined by common goals and years of mutual trust. When the deadlines are tight and the odds seem insurmountable then every setback can lead to conflict. The unity of the team will be now seriously tested. The commander of the mission is in charge of relieving these pressures*."
> [*Voice over in a Soviet space program documentary*][2] (Ligema dir. 2015, min. 29:15)

CubeSats have no commanders or crew; they are not piloted but programmed to perform specific in-orbit tasks. ESTCube initiative was started by a generation that has grown up in the Soviet Union, and ESTCube-1 was partially conceived like a spacecraft crew-like mission, composed by commanders, officers and experts of different shorts. The imaginary and narrative of the project shifted as a younger new generation took over the leadership roles during ESTCube-2 development, leaving the soviet union space program references behind them. What are the core values of this community of young practitioners, amateurs, students and space enthusiasts? We will explore ESTCube values through three main areas: hackerspace and CBPP values; open communication; hands-on education.

The reported two main factors that are attracting people to makerspaces are socializing and learning. (Moilanen 2012) Socializing is a very strong motivation to concur at makerspaces, and a group of students interviewed during a visit to their 'lab' space at Physicum (University of Tartu School of Physics) reported meeting their peers as an extra motivation to come and work on the CubeSat, while they also organize there plans to share leisure time together once they are done with their work of the day. Generally, during the several hours that the author stayed at their 'lab' space the assisting members of the project looked cheerful, communicative, and very friendly to each other, while sharing the work they have been

[2] Official English language subtitles on the documentary.

performing during the previous days, working together to solve some issues, or just sitting behind their laptops. We were also informed that group binding has one other positive consequence for the project; students get very attached to the initiative, so they keep on working and participating for more extended periods, which increases the amount of work that each member returns to the project. Besides, everyone chooses in which area to contribute, on a volunteer work basis, and with team leaders coordinating the tasks inside each subsystem of the CubeSat.

In another hand, when the author met a group of ESTCube members Finnish Satellite Workshop 2019, they mostly behaved like a cohesive group, moving together, sharing meals, filling a row of seats during the presentations and many of them wearing distinctive hoodies with ESTCube logo. I noticed the presence of at least two more groups of young CubeSat communities that moved together during the workshops wearing hoodies with the distinctive logos of their projects, which suggested that the makerspace and CBPP value set that is observable in the ESTCube community, is also applicable to other CubeSat initiatives that may be mostly formed by young students sharing experiences and work in makerspace-like facilities.

ESTCube community is also very active in social media, posting updates on their informal meetings, and they report to have groups of friends inside ESTCube community with whom they spend leisure time together in activities like watching movies, play video games, or to have barbecues. They organize and participate in hackathons, like Garage48 SpaceTech 2019, that is already the fourth time that is organized. Students are working on the project voluntarily, the same as amateurs and practitioners do; no one is getting paid for their work.

Open communication is an important aspect of makerspaces and CBPP communities. Sharing means of production, ideas, or projects, demands coordination efforts. In the case of ESTCube, communication is important internally, among team members and team leaders, and externally, to communicate their scientific and educational activities to both the general public, using social and generalistic media, and to the scientific community, by publishing their work in journals or conference papers.

Communication activities from ESTCube have been well documented. Olesk (2019) published a case research study titled 'Mediatization of a Research Group: The Estonian Student Satellite ESTCube-1', explaining the communication skills development and improvements of the communicational practices of ESTCube community. Olesk arrive to the conclusion that ESTCube-1 research group was a modelic and highly visible example of good science communication, a distinguished feature for science-funding bodies. (Olesk 2019)

The crowdfunding campaign of ESTCube-2 has also been well document in a publication from Kalnina et al. (2018). Lessons learned and the strategic communication plan to gather enough public visibility, and reach the funding goals of the campaign, have had a great impact in the willingness from ESTCube management to continue promoting the development of appropriate scientific and social media communication skills among its members. Communicating empirical lessons learnt from ESTCube-1 experience was the targeted goal of Slavinskis et al. (2015) publication, aimed to the space research community.

learning is a very important part. A newcomer may spend up to one year just getting used to the project and learning how to perform his/her tasks. Besides, hands-on education is one key driver of their success. (interview)

ESTCube members organize and take part in multiple hands-on education events. ESTCube's Science Task Force (Teadusmalev) is a *summer camp created in 2012 from Estonian Student Satellite Program*. Science Camp (Teaduslaager) is *part of Tartu Observatory Summer Academy performing traineeships.* There are also other traineeships in Estonia and abroad. Workshops, presentations, science divulgation activities are also organized. ESTCube visited more than 30 schools in Estonia during the last years. Robotech is also one of Estcube favourite events, where it has a stand and are always looking for recruiting people there. Hackathons like SpaceTech 2019 are also a usual part of the project.

4.3. Governance

> *The aim and inspirational goal of ESTCube is not other than to achieve a sustainable, well fit for our solar system interplanetary travel propulsion system. A means to go and maybe colonize other worlds, with Mars in the spotlight.*
> [*Mart Noorma during a TV interview]*[3] (Ligema dir. 2015, min. 12:40)

We have imagined many ways in which humankind could possible conquer outside worlds, and colonize other planets. Each time has its dominant mental models on how we dominate and conquer nature, and those values infuse the way we believe that we will travel through the universe. Usually, big size spacecrafts propelled by fossil fuel engines and developed by big states or corporations investing heavily in development and building such technologies are the vivid images we used to have on space travel. However, since 1968's first man landing on the moon, everything came to a halt; no human has stepped into another world, or even back on the moon surface, for instance. Maybe, the mental models that we have on how space exploration should take place were wrong, and space colonization should take place under different organizational and technological dispositions.

In ESTCube-1 CubeSat all subsystems and payloads were custom built mostly using commercial off-the-shelf (COTS) components. (Slavinskis et al. 2015) The satellite consisted of an attitude determination and control system (ADCS) that determines and modifies satellite's alignment; an onboard camera (CAM) for taking images of the Earth and the unreeled tether; a command and data handling system (CDHS), which is the satellite's main onboard computer; a communications system (COM) for uploading and downloading data; the electrical power system (EPS) that provides electrical power for the satellite; a payload

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[3] Official English language subtitles on the documentary.

(PL), which hosted the satellite's experiment module containing the tether and everything else related to the experiment; the satellite's structure (STR) upon which all other subsystems are mounted; and the ground support, consisting in the satellite's ground station (GS) and mission control system (MCS) that are used to communicate with the CubeSat. Each team was allowed to make their own design decisions independently. However, a later approach shows that it would be better “if all subsystems should follow a unified architecture and use common components and development tools where applicable, to allow reusability, to save development time, and to facilitate mobility of team members between subsystems”. (Slavinskis et al. 2015)

In ESTCube-2 development, focus on integrated parts (bus) built in-house, with integrating electronics and software of AOCS in the onboard computer and modularized firmware, a flexible structure (payload broke on ESTCube-1 mission), some ADCS sensors built in the house and others based on off-the-shelf products, and the primary communication system integrated circuit built entirely by a US firm. After using a rigid structure with over-modularized subsystems and re-building parts taken from external companies in ESTCube-1, integration of critical subsystems along with entirely in-house development on some subsystems and off-the-shelf for others seems to be the main evolutions in the satellite design, that is correlated with the evolution of ESTCube governance. Many of these choices are a direct response to the most traumatic event they have had.

There was a critical moment during the last phase of development of ESTCube-1 when it was decided to speed up the finalization of ESTCube-1 CubeSat in order to secure a launching spot. The main payload failed to perform its task once in orbit. It also broke into pieces during one of the stress tests, so it was a foreseeable outcome. They changed their philosophical approach to satellite development and prioritization.

Securing a launching is nevertheless very complicated, the CubeSat should pass many tests, protocols and standard requirement, each version of the CubeSat standards is better suited for different launchers, so the first decision on which version of CubeSat is going to be adopted have to take into consideration the targeted launcher. In fact, the “version of the CubeSat Design Specification [CSD] was selected for its standardized modular quality towards its “integration with the launch vehicle””. (Lätt et al. 2014) But launchers are not taking off often, and not securing a spot in a launcher early enough may cause many problems and internal tensions.

According to Moilanen (2012), near half of makerspace communities have 20 to 50 members. The author has identified 22 vital ESTCube developers coming from ESTCube-1, or the ‘core group’, that either team leaders of CubeSat sub-system, or part of the project development and management, or participating in ESTCube spin-offs, or having critical positions in ESTCube related organizations, especially in universities, ministries, special or space committees, European Union scientific bodies, and usually performing many of these roles at the same time. The list includes the leaders of the nine ESTCube-1 sub-systems; more than half of the members (5 out of 9) of the academic counseling of the program; almost half of ESTCube-1 core members (9 out of 22) involved in startup and entrepreneurship spin-off activities; almost two thirds (5 out of 8) of Estonian Student Satellite Foundation board members; two thirds (6 out of 9) of the members of the Department of Space Technology at Tartu Observatory.

The three main actors during the ESTCube-1 era are coming from the three key places that have supported and contributed the most the the project: Mart Noorma, who was the vice-rector of University of Tartu, Anu Reinert, who was director of Tartu Observatory, and Jouni Envall from Finnish Meteorological Institute that was the team leader of the main payload of ESTCube-1, the E-sailing prototype. The young leaders of ESTCube-2 are coming from different team leaders of ESTCube-1, with ESTCube foundation’s management board members Kadri Bussov and Hendrik Ehrpais assuming the most visible roles of the project, and three former ESTCube-1 team leaders as members of the supervisory board of the foundation.

One of the makerspaces features is to provide open access to infrastructure and means of production that based on available local fabrication technologies. In the case of ESTCube, the makerspace infrastructure is distributed between different spaces, that are differently used during the different stages of development of their CubeSats. The two places that resemble more a makerspace are the room lab that ESTCube has at the Physics department of the

University of Tartu and the space they also have at Tartu Observatory. There, team members can work together in the development of the project. Besides that, there are other universities abroad that are partners of the project, and they facilities are also used as ‘remote’ makerspace areas. During the development of ESTCube-2, each of this ‘remote makerspaces’, located in different organization (mostly in universities) in different countries and cities, is hosting the development of an individual subsystem of the CubeSat. There are also testing labs where the test of the components and the CubeSat are performed. Testing as a crucial aspect of CubeSat development, as the satellites has only one change to make it into orbit, and they also have to meet very stricts international standards in order for the CubeSat to be accepted onboard a rocket launcher. There is also the launching place, that in the case of ESTCube-1 was located at the French Guyana. A delegation of ESTCube travelled with the CubeSat in order to perform the last test before launching during the ‘launching window of opportunity’ that lasted for around two weeks, period during which ESTCube delegation has access to lab facilities abroad, delocalizing the last steps of development.

For online communications and development, ESTCube has recently adopted a common digital platform called Fleep. Used as a communication platform for distributed networks organized in groups to solve tasks and address issues. It has several integrations to their repositories (GitHub; Google Drive; Dropbox), CAD files, google docs, task management (Trello), video calls, etc. The embedded search tools of Fleep allows quick access to former conversation, stored files, etc.

There is an important amateur component in ESTCube members. Semi-pro & amateur compilers of space info freely available from some space-related institutions are ruling some of the best online databases on nanosatellites (nanosats.eu); one of then comes from ESTCube program. The amateur and hobbyist areas include radio, robots, Science Olympics, programming, or making.

According to a comparative analysis on the politics of foundation, “most foundations in Estonia can be classified as operating foundations, though their functional difference from non-profit associations is not always clear.” (Lagerspetz and Rikmann 2006, p.144) The second sort of Estonian foundations are operating for the benefit of some groups or communities, and the third one is established by governments at different levels and both operating and grant-giving, for the purpose of “decentralize governance, to guarantee the independence of specific policy areas, to enable partnership with private capital and to allow the participation of non-political professional people in decision making.” (Lagerspetz and Rikmann 2006) Estonian Student Satellite Foundation inherits most of these categories. It is an operating foundation because it builds satellites, and it has targeted communities; Estonian space engineers and the startup ecosystem, along with the space research community related to the University of Tartu and the Tartu Observatory. Space research in Estonia is organized through public, private and hybrid bodies. Some of these bodies emerged with the sole task of supporting Estonian space research, i.e. Space Studies Support Group, Space Committee, Space Policy Working Group, Estonian Space Office, while others just incorporated space research to their multiple responsibilities i.e. Enterprise Estonia and some Ministries.

The Estonian Student Satellite Foundation is “legal body for developing the satellite and representing the team”. (Kalnina et al. 2018) Its origin comes from a very practical reason: how to administer a big donation. It was established at the beginning of the year 2017, and since then it has become to center of gravity of the whole initiative, as ‘the most pressing problem that the program faces comes from the shortage of funds. Although CubeSats are considered relatively cheap (...) they are still significant burdens for a student projects and independent volunteer organizations”. (ibid.) Currently, ESTCube-2 costs are mostly covered by Estonian Student Satellite Foundation, but as the project is based on voluntary collaboration, the budget is spent in the technology and other related expenditures, while the salaries of the practitioners are covered by other organizations.

ESTCube uses an ad hoc and agile decision making approach to solving issues, and consensus-based decisions for design and other choices that will affect the CubeSat. The foundation takes the lead, but they consult with each and every member that may have an informed opinion. All sub-system teams are engaged discussing the main choices between during the early stages of design, opening all issues for a discussion, and all members are involved in the processes that lead to the biggest decisions, like choosing the launch provider. (Slavinskis et al. 2015)

The hardest thing to fund is the launch of the Satellite. It costs 250,000 euro for ESTCube-2 3U CubeSat and it costed 75,000 euro for ESTCube-1 1U CubeSat. No sponsor or donor wants to contribute to those ‘fuel expenses’, as it doesn’t provide a great return in reputation, public visibility or personal pride. They usually ask to fund other areas related to the hardware. Three practices connected with OSH development were adopted by ESTCube. Crowdfunding, that requires the development of a working prototype as in the case of ESTCube-2, during which crowdfunding campaign at Estonian platform ‘Hooandja’ fundraising was also used. Product partnership provides (meager) monetary resources, can help perform some services or give free components, free legal advice, and especially useful and prominent is that partner companies can make a discount of their services to fabricate parts of the CubeSats. Sponsoring, grants, donations and public research that appeal to the public interest of the project, arguing that it would benefit society, humanity, or any other abstract idea that can be subject of public attention, while also providing by this practices jobs or livelihoods for the core developers, as in the case of research grants or academic positions at universities. Just to illustrate the case, we will show two of the prominent programs and grants documented by Lätt et al. (2014): the European Space Agency has supported ESTCube-1 via the European Space Agency Plan for European Cooperating States (PECS), the European Commission has supported ESTCube-1 through various projects, and through the Erasmus training programme.

4.4. Business models

> *[Erik] This circuit board has one hundred rows of components. Can you imagine what a machine would cost that could involve hundreds of different components?*
> *[Jaanus] Erik, it is not my fault that you designed a board with one hundred components.*
> *[Erik] All boards can't be as simple as yours.*
> *[Jaanus] Design for manufacture.*
> *[Erik] Satellites are not for manufacture.*
> *[Jaanus] But they should be.*
> *[Erik] But they are not.*
> *[Jaanus] Within ten years they will be.*
> *[Erik] They won't. Maybe in twenty.*[4]
> (Ligema dir. 2015, min. 21:19)

Are CubeSats designed and produced for manufacturing? According to FOSH general design principles, minimizing the amount of material used, minimizing the number of parts, minimizing the complexity of the tool and using a parametric design are all important characteristics. Moving into a future where DGML mode of production has succeeded by the increased use of OSH production through local digital manufacture practices, 'design for manufacture' would win the argument.

ESTCube is not a fully defined project yet. It was conceived in three phases of development, that would coincide with the manufacturing and launching of three different ESTCube CubeSats. At the moment, the project is half-way, at the end of the development phase of the second ESTCube CubeSat. According to their value proposition and route map, once the third ESTCube CubeSat has been launched and tested, they will have a mature technology around which create a business environment. For now, their community of Estonian space engineers is going through their hands-on education programs, gaining experience and working on the first spin-off companies, that seems to be, in their majority, and as it would be expected, going through their initial stages.

[4] Official English language subtitles on the documentary.

The path of ESTCube into a possible OSH development has some milestones that are already here to be used and followed. CubeSat is an open platform, to anyone who wants to build a CubeSat, with all the specifications of its different versions freely available online. For ESTCube-2 it is planned to use open source parts. To ESTCube, open software is always preferable, and the student orbit control team want to publish simulator environment. MatLab dependency, Andris moved to Python (OSS) after some days away from university and its license-based access to MatLab. He is not going to come back. MCS and GS technologies are the easier to share, so are the ones experimenting with Open Source products. They are already using some open source for-satellite software (KubOS). Copernicus open data is already been used by one company with an ESTCube member. They have identified as a good practice to regularly document the code and keep user manuals up to date. (Slavinskis et al. 2015) The documentation of the CubeSats is irregular and unorganized, but fragments can be found in published papers, academic thesis, conference presentations, social and generic media online, and we can say that ESTCube core values agree with OSS and OSH principles, but not conscious effort has been invested in a detailed documentation of the projects, also because only one person who participated in the project is an active OSS and OSH collaborator.

ESTCube IOD CubeSats in three stages is still to fulfil phase two, as ESTCube-2 is not fully developed yet. Summing this to ESTCube-1 failure of e-sailing experiment, we may argue that the project is not yet out from conceptual and prototyping phase, and following Bonvoisin et al. (2017) it can be said that the expected level of openness of the nanosatellites is low, and the different levels of openness should be expected to be unevenly distributed through the different sub-system of the CubeSats, been as it is an open platform of mechatronic engineering, with many COTS used in the electronic parts, and other part slike the main mechanical payload containing the tether being developed in-house.

ESTCube can also be considered a OSH project, as it provides scientific experimental equipment for the Finnish Meteorological Institute to develop and test E-saling; it provides academic collaborative research and hands-on learning; it fosters an innovation business ecosystem; it designs and manufacture a complex technological tool, the CubeSat, that using electronics, software, and non-electronic components, i.e. a mechatronic product. Moreover, it develops products that have potential to become OSH: ESEO camera, the plasma break and e-sailing technologies that are targeting profitable sectors after a successful Estcube-3 experiment.

Been a small country, no incentives to spend time documenting their hardware (so they can open it) as most people interested are part of their ecosystem, business models are not well developed, standards on payloads and components are still missing. As most of what they design is produced by their 'sponsors', and their main focus is in scientific research and testing experimental payloads, no incentive to open source their CubeSats, as they are not meant to be copied or forked. The state of the art of CubeSats is not yet. The sector didn't get out from the experimental phase yet.

At least one but no more than two of ESTCube spin-offs seem to be profitable, while three of them are into (or back into) incubator phase (ESIC), and there is a case of a former member of ESTCube-1 team that is a OSH entrepreneur, but who has to work in lab companies and used to work at ESTCube's spin-off Crystalspace for a living, there is one company using open data from Copernicus to map fields with a Estcube top developer in their team.

At Technopol's ESA's business incubation program are currently they have 6 start-ups, two from ESTCube members and another with a ESTCube member in the crew; Spaceit, Crystalspace, and Kappazeta. It is not an uncommon strategy that older companies can come back and develop something new in an incubator program, as the market seems to be not mature for their products.

ESTCUBE spin-off companies are Krakul OÜ, Crystalspace OÜ, Radius Space OÜ, Spaceit OÜ, Taevanael OÜ, Cubehub OÜ, and PL SPACE OÜ. They have business models well suited for OSH ecosystems, as they build hardware products, assembly kits, components and complementary parts for CubeSats.

5. CONCLUSIONS

The ESTCube foundation may be seen as a low-cost integrator of modular contributions during complex digital fabrication. ESTCube proves that the threshold for participation in CBPP initiatives is so low that even (high)school students can contribute to the development of a project as technically complex as designing, developing and building a CubeSat. Estonian Students Satellite Foundation may be a materialization of CBPP ecosystems in the realm on digital fabrication. It is not what Zimmermann (2014) says, neither what Bauwens, Kostakis and Pazaitis (2019) describe in their CBPP ecosystem where all the foundations described are for-benefit associations that provide infrastructure and coordination for OSS or digital communities. ESTCube contributive communities and entrepreneurial coalitions are engaged in the production of complex physical objects, i.e. digital manufacturing, while Linux Foundation, Mozilla Foundation, Free Software Foundation, Wikimedia Foundation, Wordpress Foundation are part of open-source software projects, while Enspiral Foundation does not produce physical objects. The WikiHouse Foundation resemble some of the aspects of Estonian Student Satellite Foundation (list them) back with salient differences (list them)

ESTCube seems to be, in many aspects, a further evolution of hackerspaces and peer-production, into highly complex specialized manufacturing. Estcube would be good for research, testing, prototyping, standardize, innovating, but not for producing. To manufacture CubeSats on a larger scale, a fabric of enterprises should come along, benefiting from Estcube knowledge, getting knowledge transfers by hands-on educated workforce produced by estcube and later used in the related businesses. ESTCube's community of producers and enterprises ecosystem is not mature enough for systematic production, and it would take at least until after successful completion of ESTCube-3 mission to have the mature technology that could be standardized and commonly used by other CubeSats. We can conclude that ESTCube is in the midst of their ‘prototype’ phase, with a significantly lower average openness than those in production phases.

Been a small country, no incentives to spend time documenting their hardware (so they can open it) as most people interested are part of their ecosystem, business models are not well developed, standards on payloads and components are still missing. As most of what they design is produced by their ‘sponsors’, and their main focus is in scientific research and testing experimental payloads, no incentive to open source their CubeSats, as they are not meant to be copied or forked. The state of the art of CubeSats is not yet. The sector didn’t get out from the experimental phase yet.

Projects like UPSat, that started from the very beginning using and promoting open source tools can act as guides into that path, but have not a big community of open source satellite developers to work with, which difficult their interaction with other initiatives as Estcube, that will favor open source practices if the costs to switch platforms were affordable from a networking perspective, i.e. to keep interoperability with their key partners.

It seems that the same conditions that make grassroots movements in other sectors of activity go for the open source way, (lower costs) it is forcing estcube to take the opposite direction. Lack of funds, dependency on partners, sponsors who work with closed licenses and business models, force estcube to use the tools they can get from them, as they have not the capacity to build everything by themselves.

ESTCube constitutes an extreme case study, because too much-coordinated effort is put during years by more than a hundred persons working in the design, building, and launching of a small complex object that once it is ready, it is never to be seen again. Its main aim is to perform one experimental task, and for that task to be performed in Earth orbit, a thriving cbpp community works under very similar patterns as typical open-source software communities. It exemplifies an extreme case of OSH manufacturing, as CubeSats are very small and extremely complex products that take long development time and can only be used once; once launched, the information that arrives from the CubeSat to mission control stations are the only proof of their existence

Is it a critical case study? To show a case of an emerging CBPP ecosystem in the field of DGML, it may confirm that OSH can take place in CBPP ecosystem following a similar set of three institutions as in the most paradigmatic OSS cases as Wikipedia or Linux. In such fields as CubeSats development, with distributed networks of modularized collaborations to design and build a complex (mechatronic) artifact that demands the use of highly specialized scientific knowledge, CBPP ecosystems may also be providing many advantages regarding the usual organizations in the field, as national space programs and space corporations. This critical case shows the superiority of CBPP not only in digital information production but also in digital manufacturing.

In the case of ESTCube space research and nanosatellites manufacturing, many of the key components of the DGML model are present. The spillovers of these ideas, incarnated in open source projects and other peer-reviewed collaborative practices, seem to be so pervasive that can be easily adopted in high-tech space research fabrication practices.

ESTCube ecosystem from a CBPP perspective consist of: an emerging productive community; under-developed commons-oriented entrepreneurial coalition(s); a maturing for-benefit association. The key aspect here is the stage of development of their CubeSat plan: ESTCube-1 failed to perform their main payload scientific experiment, and currently they are at the end of the development phase of ESTCube-2, that is the prototype of ESTCube-3, which should be the mature CubSat that could be ready to be documented as OSH, thus enabling the development of the commons-oriented entrepreneurial coalition(s) of ESTCube (CBPP) ecosystem. At that point, ESTCube could be considered a clear case of DGML.

The author would argue that theoretically speaking, the case of ESTCube satellites represents another 'design-embedded sustainable DGML product', as a community-based desktop fabrication of complicated technologies seems to embody most of the positive incentives for sturdy long-term fabrication oriented to use value.

Explain very carefully how ESA environment is both a requirement to take part in space research and a heavy burden for projects like ESTCube.

SUMMARY

This thesis aimed to research a case study where the convergence of "digital commons" and local manufacturing for the fabrication of CubeSats enables a community of space researchers it to take part in an area of activity where the barriers to entry used to be significantly high. In the context of a small state that lacks the resources to have its own national space agency, a foundation of student has managed to design, build and launch the first ever Estonian satellite (not only nanosatellite but of any kind). ESTCube project has produced scientific literature, space engineers with hands-on experience (let's remember how important and difficult in the Estonian space research context), and now they are pointing out to the moon. ESTCube-2 is the preliminary test before sending a CubeSat to orbit the Moon. Not small goals at all for a not very big foundation.

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